APPLICATION OF SUPERCONDUCTING MOTORS TO SUPER CAVITATING HYDROFOIL PROPULSION

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ABSTRACT

The use of superconductors in the field windings of large synchronous rotating electrical machines virtually eliminates the need for magnetic iron core material and hence reduces the size and weight requirements for a given power level. This possible reduction in size and weight can be exploited in the propulsion of hydrofoil craft. Present hydrofoil propulsion schemes all have serious salient disadvantages that have stimulated the search for a better propulsion scheme for hydrofoil craft. This thesis proposes the use of a novel dual armature superconducting induction motor. The motor would be encased in a water tight pod and placed on the end of a foil strut and directly drive a super-cavitating propeller. A mathematical model is developed and the size and parameters of a 21000 horsepower motor are determined. The resulting model is statically and dynamically analyzed.

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I INTRODUCTION

In conventional displacement type ship hull forms, the power available within the hull can be readily converted to propulsive thrust by conventional direct drive propellers. However, in a hydrofoil type ship hull form, the mechanism of converting the available power within the hull to propulsive thrust is no longer a simple matter. When the hydrofoil vehicle 'flies' (becomes foil borne), the hull is lifted out of the water and conventional types of propulsion are no longer feasible. A simple direct drive straight rotating shaft with a propeller on the end will not suffice.

An assortment of alternative hydrofoil propulsion schemes have been proposed or developed:

1. The water jet system scoops up water at an inlet in a forward foil strut and ejects this water at high velocity out the stern, thus providing the propulsive thrust. This arrangement requires large amount of internal hull volume for water ducts and pump machinery and places large amounts of water weight inside the hull. Additionally, this method has a low efficiency at low velocities.
2. Another scheme utilizes a mechanical gear train containing right angle gears to drive propellers mounted on the foil struts. This scheme suffers from a very high initial cost and a low mean time between failure, hence unreliability and high maintenance costs.
3. Air propellers, turbo-props, and other aerodynamic propulsors all have los efficiencies in the speed ranges anticipated for hydrofoils in the near future.

4. Electric motors can be placed in pods on the end of the foil struts and drive propellers directly. This method eliminates the objections of the preceding schemes, but introduces a new objection of its own. The pod of the size required for a conventional motor would produce extremely high levels of hydrodynamic drag in the speed ranges of the hydrofoil vehicles.

While all of the above methods of propulsion are feasible and can be utilized, there is much needed improvements before hydrofoil vehicles can compete economically with the displacement type vessels. Much research and development is being done to improve on each type of propulsion system. In particular, the motor in the submerged pod system has been vigorously pursued with emphasis on reducing the required size of the motor through the use of super conduction technology.[4,5,6,7]

The first attempt at applying super conducting materials to motors utilized Faraday's homopolar concept.[7] It has the characteristics of low DC voltages with high current densities.[4,5] The high DC current densities of the homopolar devices complicates the power transmission and switching problems and requires some sort of liquid brushes in the motor. Several different configurations using the homopolar concept are discussed in reference (4).

The recent trend in super conducting machines has been toward the use of AC synchronous devices. While AC machines lack the high starting torques which are characteristic of DC machines, they have a superior reliability in a marine environment and the power transmission and switching problems are much less than for DC machines. The AC super conducting machines most considered are of the type with a stationary three

phase armature (stator) and a revolving DC field (rotor) consisting of super-conducting winding in a Dewar bottle.[4,5,7]

A recent development in AC super-conducting machines is a family of machines which utilizes two armatures and a super-conducting field winding.[1] The field winding and one armature, which may or may not be wound, rotate, and the other armature is fixed (stator). One motor configuration utilizes a superconducting field which is free to rotate and is mechanically unconstrained except for its own inertia, it responds only to the applied electrical torques and its inertia. Both armature windings are wound in a three phase manner, one armature is fixed (stator) and receives the input electrical power, and the other, positioned between the stationary armature and the rotating field, develops the mechanical output torque in the same manner as a wound rotor induction motor does. This latter configuration is the topic of this thesis. It will be mathematically developed and applied to the propulsion of a hydrofoil vehicle. Its static and dynamic characteristics will be presented. The resulting size of the motor will demonstrate that it is compact and will significantly reduce the hydrodynamic drag of the pod to an acceptable level.

II PHYSICAL DESCRIPTION OF THE DUAL ARMATURE MOTOR

The motor to be studied by this thesis utilizes a four pole rotating field that is mechanically unconstrained, except for its own moment of inertia. This field will be of the super conducting type and will be encased in a Dewar bottle and cooled by liquid helium. It will be excited by a DC current source. In general, the design of the field will be similar to the field winding developed at MIT.[13] This field will be capable of producing conventionally unachievable magnetic flux densities due to the large current densities that are made possible by the super conducting material. The superconducting winding will hence forth be referred to as the field.

Surrounding the field and attached to it is a damper shell. This shell will provide the start up torques and damp out dynamic oscillations. The damper shell and the field together will hence forth be referred to as the rotor.

Surrounding the rotor will be a three phase, four pole winding. This winding will contain no magnetic core material and will contain only enough steel or other material to provide mechanical support and rigidity. It will be free to rotate relative to the rotor and to the motor frame. It will be attached to a shaft from which mechanical power may be extracted and supplied to the load, in this case a propeller. The electrical terminals of the winding will be brought outside the motor through slip rings. This winding will hence forth be referred to as the shell.

The rotor and shell are surrounded by yet another three phase four pole winding that contains no magnetic core material. It is

rigidly attached to the motor frame and contains only enough steel to provide mechanical support and rigidity. This winding will hence forth be referred to as the stator.

Surrounding the stator is a shield made of a magnetic core material. Its purpose is to contain the magnetic fluxes within the motor and provide a more efficient return path for the fluxes. If the shield were not present the rotating flux field would extend beyond the motor and possibly induce hazardous voltages in the surrounding areas which could present a hazard both to equipment being operated in the vicinity and to man.

The stator is now surrounded by a water tight enclosure, called the pod, that will keep the motor dry and minimize the hydrodynamic drag. The magnetic shield could be a part of the pod body.

In operation, three phase electrical power will be provided to the stator winding which will produce a revolving magnetic field. The rotor will lock into synchronism with the stator field and in effect become a virtual magnetic core by producing a rotating magnetic field far greater than could the air core stator by itself. The shell will act as a wound rotor induction armature under the influence of the rotating magnetic field and drive a super cavitating propeller directly as shown in figure (1). Figure (2) shows the geometric configuration of the field, damper, shell stator and shield.

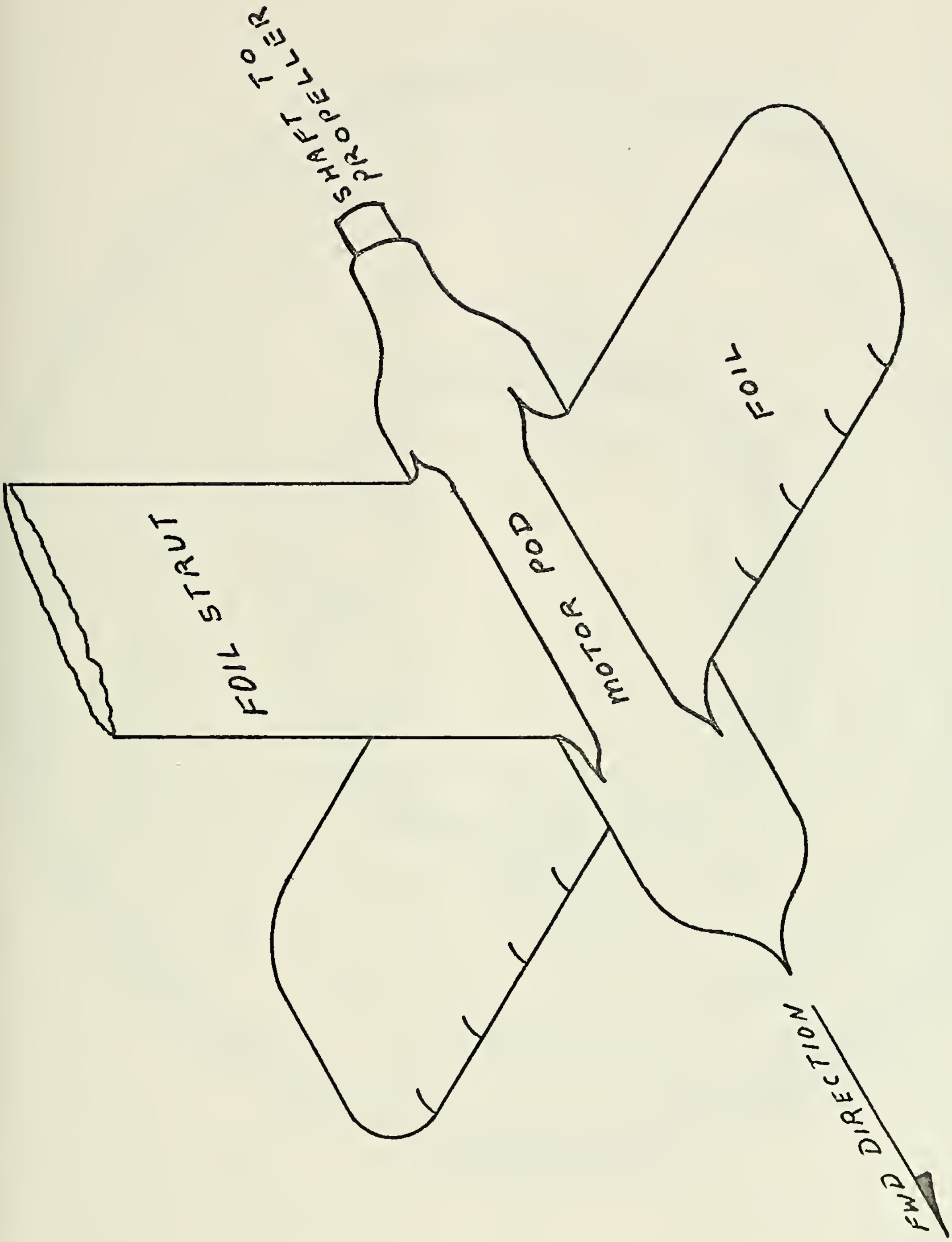
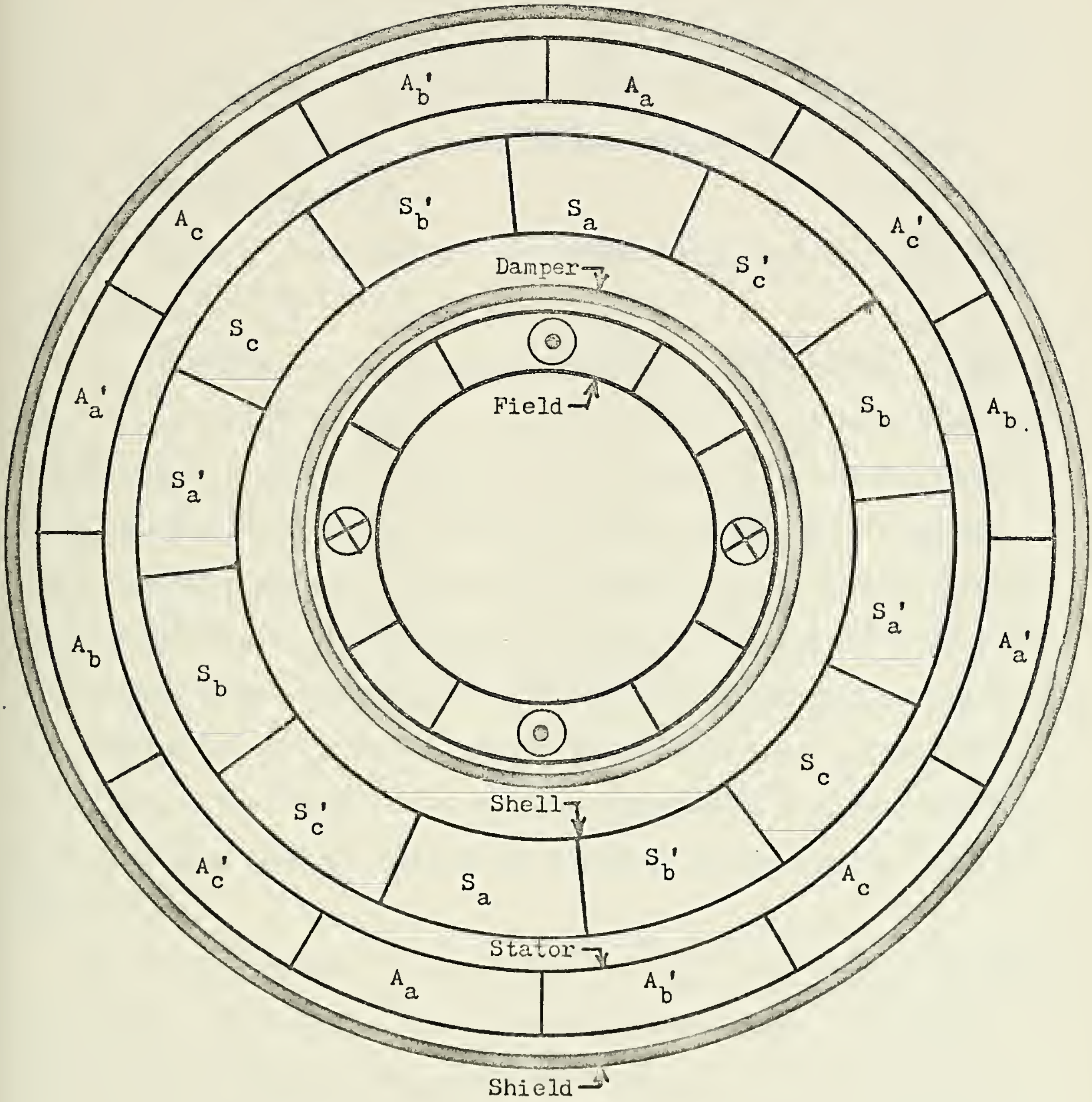


figure (1)



A_b'
A_a
A_c
A_c'
S_b'
S_a
S_c'
Damper
S_c
Field
S_b
A_a'
A_b
S_a'
S_a'
A_a'
A_b
S_b
S_c
Shell
S_c'
S_b'
A_c'
S_a
A_c
Stator
A_a
A_b'
Shield

Figure (2)

III MATHEMATICAL MODEL OF THE MOTOR

The motor is modeled electrically as shown schematically by figure (3). Figure (3) shows the axes of the various windings. The rotor has a direct axis (in the direction of positive flux lines of the field) and a quadrature axis which leads the direct axis by ninety degrees. The direct axis is at an angle θ with respect to the stator 'A' phase axis as shown in figure (3).

The shell 'A' phase axis is at an angle ϕ with respect to the stator 'A' phase axis.

The various mutual inductances are assumed to be sinusoids dependent upon the angular orientation of the axes involved. The mutual inductances are maximum when the axes are aligned, zero when they are ninety degrees apart, and negative (minimum) when they are one hundred-eighty degrees apart. Equation set (1) gives the flux linkages for the various circuits when the currents in all circuits are considered. Equation set (2) gives the voltages at the terminals of the various circuits when all currents in all circuits are accounted for and the circuit relation $V_i = p\lambda_i + R_i I_i$ is utilized. The symbol p is a operator representing the time derivative d/dt. All other symbols utilized are idetified in the Glossary of Terms, Table (1).

The rather formidable equation sets (1) and (2) can be significantly simplified by performing a Park's transformation on them. The Park's transformation equations are given here as equation set (3). When the transformation of equation set (3) is applied to equation sets (1) and (2), equation sets (5) and (6) result.

Table I Glossary of Terms

Note: where a dual assignment of usage is indicated, the context should make it clear to the reader the intended usage of the symbols.

Symbols

I	Current
L	Self Inductance
l	length
M	Mutual Inductance
N	Coil Turns/ angle as defined in figure (3)
P	Permeance
p	Differential Operator d/dt
R	Resistance/ Radius
s	Slip
T	Torque
t	time
U	Dummy Variable used in the Park's Transformation Equation
V	Voltage
W	Angular Velocity
X	Reactance/ Ratio of Reactances
θ	Angle Defined in Figure (3)
λ	Flux
π	3.π4....
ϕ	Angle Defined in Figure (3)
Ψ	Per-Unitized Flux

Table I continued

Subscripts

a	Phase a/ Stator Armature
b	Phase b/ Base Quantity
c	Phase c
d	Direct Axis
f	Field
i	Arbitrary Index
j	Defined in Text
k	Defined in Text
l	Defined in Text
m	Defined in Text
o	Zero Sequence/ Synchronous Frequency/ Defined in Text
p	Per-Unitized Quantity
r	Rotor
s	Shell

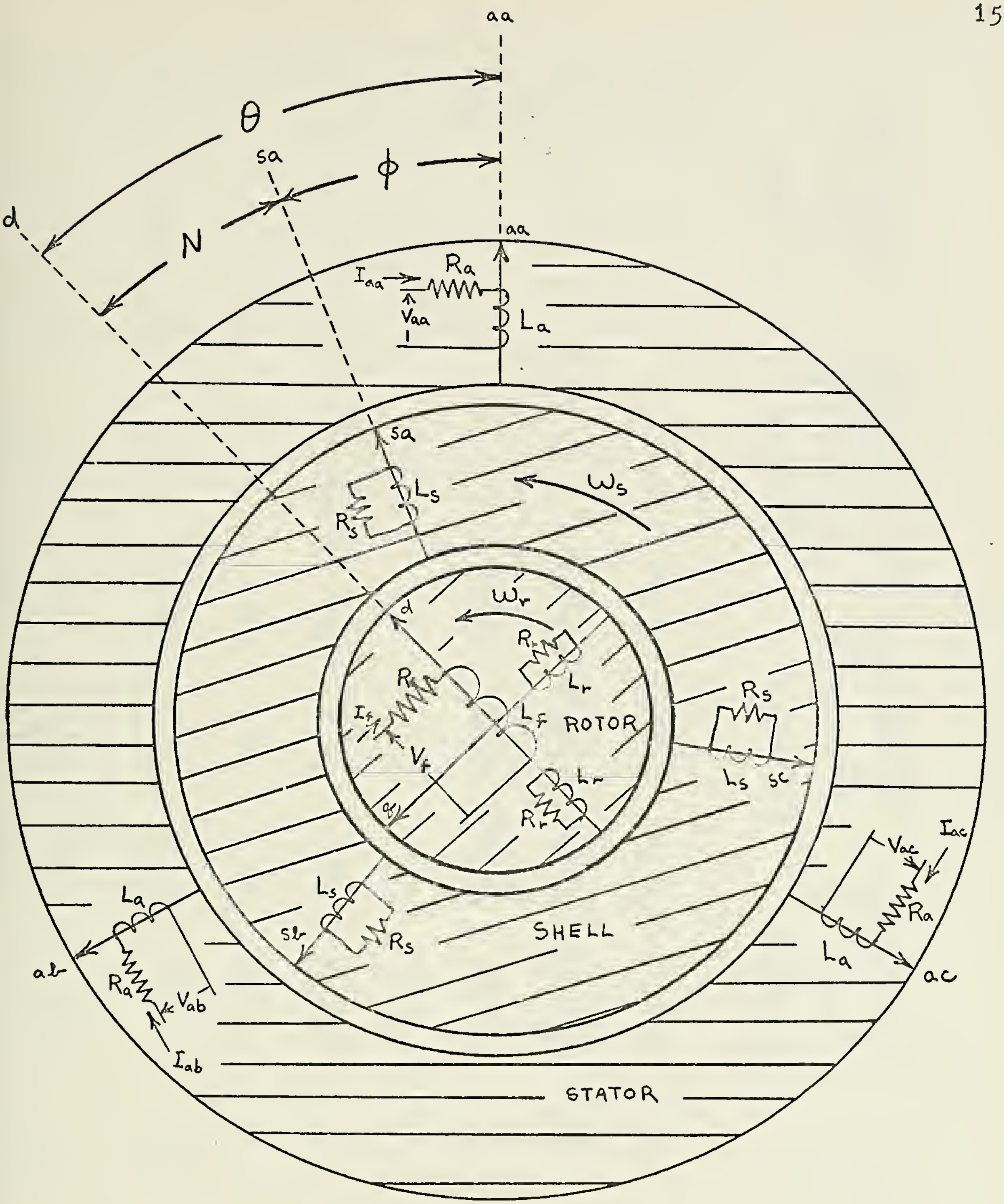

aa
θ
sa
φ
d
N
aa
I_{aa}
R_a
V_{aa}
L_a
sa
L_s
R_s
ω_s
d
ω_r
R_r
L_r
R_f
I_f
V_f
L_f
ROTOR
R_s
L_s
sc
L_r
R_r
q
I_{ac}
V_{ac}
R_a
L_a
ac
L_s
sb
R_s
SHELL
L_a
ab
R_a
V_{ab}
I_{ab}
STATOR

Figure (3)

$$
\begin{bmatrix} \lambda_{aa} \\ \lambda_{ab} \\ \lambda_{ac} \\ \lambda_{sa} \\ \lambda_{sb} \\ \lambda_{sc} \\ \lambda_{rd} \\ \lambda_{rq} \\ \lambda_{f} \end{bmatrix}
=
\begin{bmatrix}
L_a & M_{aa} & M_{aa} & M_{as}C_{\phi a} & M_{as}C_{\phi c} & M_{as}C_{\phi b} & M_{ar}C_{\theta a} & -M_{ar}S_{\theta a} & M_{af}C_{\theta a} \\
M_{aa} & L_a & M_{aa} & M_{as}C_{\phi b} & M_{as}C_{\phi a} & M_{as}C_{\phi c} & M_{ar}C_{\theta b} & -M_{ar}S_{\theta b} & M_{af}C_{\theta b} \\
M_{aa} & M_{aa} & L_a & M_{as}C_{\phi c} & M_{as}C_{\phi b} & M_{as}C_{\phi a} & M_{ar}C_{\theta c} & -M_{ar}S_{\theta c} & M_{af}C_{\theta c} \\
M_{as}C_{\phi a} & M_{as}C_{\phi b} & M_{as}C_{\phi c} & L_s & M_{ss} & M_{ss} & M_{sr}C_{na} & -M_{sr}S_{na} & M_{sf}C_{na} \\
M_{as}C_{\phi c} & M_{as}C_{\phi a} & M_{as}C_{\phi b} & M_{ss} & L_s & M_{ss} & M_{sr}C_{nb} & -M_{sr}S_{nb} & M_{sf}C_{nb} \\
M_{as}C_{\phi b} & M_{as}C_{\phi c} & M_{as}C_{\phi a} & M_{ss} & M_{ss} & L_s & M_{sr}C_{nc} & -M_{sr}S_{nc} & M_{sf}C_{nc} \\
M_{ar}C_{\theta a} & M_{ar}C_{\theta b} & M_{ar}C_{\theta c} & M_{sr}C_{na} & M_{sr}C_{nb} & M_{sr}C_{nc} & L_r & 0 & M_{rf} \\
-M_{ar}S_{\theta a} & -M_{ar}S_{\theta b} & -M_{ar}S_{\theta c} & -M_{sr}S_{na} & -M_{sr}S_{nb} & -M_{sr}S_{nc} & 0 & L_r & 0 \\
M_{af}C_{\theta a} & M_{af}C_{\theta b} & M_{af}C_{\theta c} & M_{sf}C_{na} & M_{sf}C_{nb} & M_{sf}C_{nc} & M_{rf} & 0 & L_f
\end{bmatrix}
\begin{bmatrix} I_{aa} \\ I_{ab} \\ I_{ac} \\ I_{sa} \\ I_{sb} \\ I_{sc} \\ I_{rd} \\ I_{rq} \\ I_{f} \end{bmatrix}
$$

Where:

$C_{\phi a}=\mathrm{COS}(\phi)$ $C_{\theta a}=\mathrm{COS}(\theta)$ $S_{\theta a}=\mathrm{SIN}(\theta)$ $C_{na}=\mathrm{COS}(N)$ $S_{na}=\mathrm{SIN}(N)$

$C_{\phi b}=\mathrm{COS}(\phi-\frac{2\pi}{3})$ $C_{\theta b}=\mathrm{COS}(\theta-\frac{2\pi}{3})$ $S_{\theta b}=\mathrm{SIN}(\theta-\frac{2\pi}{3})$ $C_{nb}=\mathrm{COS}(N-\frac{2\pi}{3})$ $S_{nb}=\mathrm{SIN}(N-\frac{2\pi}{3})$

$C_{\phi c}=\mathrm{COS}(\phi+\frac{2\pi}{3})$ $C_{\theta c}=\mathrm{COS}(\theta+\frac{2\pi}{3})$ $S_{\theta c}=\mathrm{SIN}(\theta+\frac{2\pi}{3})$ $C_{nc}=\mathrm{COS}(N+\frac{2\pi}{3})$ $S_{nc}=\mathrm{SIN}(N+\frac{2\pi}{3})$

Equation Set (1)

$$
\begin{bmatrix} V_{aa} \\ V_{ab} \\ V_{ac} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ V_f \end{bmatrix}
=
\begin{bmatrix}
pL_a+R_a & pM_{aa} & pM_{aa} & pM_{as}C_{\phi a} & pM_{as}C_{\phi c} & pM_{as}C_{\phi b} & pM_{ar}C_{\theta a} & -pM_{ar}S_{\theta a} & pM_{af}C_{\theta a} \\
pM_{aa} & pL_a+R_a & pM_{aa} & pM_{as}C_{\phi b} & pM_{as}C_{\phi a} & pM_{as}C_{\phi c} & pM_{ar}C_{\theta b} & -pM_{ar}S_{\theta b} & pM_{af}C_{\theta b} \\
pM_{aa} & pM_{aa} & pL_a+R_a & pM_{as}C_{\phi c} & pM_{as}C_{\phi b} & pM_{as}C_{\phi a} & pM_{ar}C_{\theta c} & -pM_{ar}S_{\theta c} & pM_{af}C_{\theta c} \\
pM_{as}C_{\phi a} & pM_{as}C_{\phi b} & pM_{as}C_{\phi c} & pL_s+R_s & pM_{ss} & pM_{ss} & pM_{sr}C_{na} & -pM_{sr}S_{na} & pM_{sf}C_{na} \\
pM_{as}C_{\phi c} & pM_{as}C_{\phi a} & pM_{as}C_{\phi b} & pM_{ss} & pL_s+R_s & pM_{ss} & pM_{sr}C_{nb} & -pM_{sr}S_{nb} & pM_{sf}C_{nb} \\
pM_{as}C_{\phi b} & pM_{as}C_{\phi c} & pM_{as}C_{\phi a} & pM_{ss} & pM_{ss} & pL_s+R_s & pM_{sr}C_{nc} & -pM_{sr}S_{nc} & pM_{sf}C_{nc} \\
pM_{ar}C_{\theta a} & pM_{ar}C_{\theta b} & pM_{ar}C_{\theta c} & pM_{sr}C_{na} & pM_{sr}C_{nb} & pM_{sr}C_{nc} & pL_r+R_r & 0 & pM_{rf} \\
-pM_{ar}S_{\theta a} & -pM_{ar}S_{\theta b} & -pM_{ar}S_{\theta c} & -pM_{sr}S_{na} & -pM_{sr}S_{nb} & -pM_{sr}S_{nc} & 0 & pL_r+R_r & 0 \\
pM_{af}C_{\theta a} & pM_{af}C_{\theta b} & pM_{af}C_{\theta c} & pM_{sf}C_{na} & pM_{sf}C_{nb} & pM_{sf}C_{nc} & pM_{rf} & 0 & pL_f+R_f
\end{bmatrix}
\begin{bmatrix} I_{aa} \\ I_{ab} \\ I_{ac} \\ I_{sa} \\ I_{sb} \\ I_{sc} \\ I_{rd} \\ I_{rq} \\ I_f \end{bmatrix}
$$

Where:

$C_{\phi a}=\mathrm{COS}(\phi)$ $\quad C_{\theta a}=\mathrm{COS}(\theta)$ $\quad S_{\theta a}=\mathrm{SIN}(\theta)$ $\quad C_{na}=\mathrm{COS}(N)$ $\quad S_{na}=\mathrm{SIN}(N)$

$C_{\phi b}=\mathrm{COS}(\phi-\frac{2\pi}{3})$ $\quad C_{\theta b}=\mathrm{COS}(\theta-\frac{2\pi}{3})$ $\quad S_{\theta b}=\mathrm{SIN}(\theta-\frac{2\pi}{3})$ $\quad C_{nb}=\mathrm{COS}(N-\frac{2\pi}{3})$ $\quad S_{nb}=\mathrm{SIN}(N-\frac{2\pi}{3})$

$C_{\phi c}=\mathrm{COS}(\phi+\frac{2\pi}{3})$ $\quad C_{\theta c}=\mathrm{COS}(\theta+\frac{2\pi}{3})$ $\quad S_{\theta c}=\mathrm{SIN}(\theta+\frac{2\pi}{3})$ $\quad C_{nc}=\mathrm{COS}(N+\frac{2\pi}{3})$ $\quad S_{nc}=\mathrm{SIN}(N+\frac{2\pi}{3})$

Equation Set (2)

$$\begin{bmatrix} U_{ad} \\ U_{aq} \\ U_{ao} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} U_{aa} \\ U_{ab} \\ U_{ac} \end{bmatrix}$$

$$\begin{bmatrix} U_{sd} \\ U_{sq} \\ U_{so} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix}$$

Equation Set (3)

$$\begin{aligned}
V_{ad} &= p\lambda_{ad} - p\theta\lambda_{aq} + R_a I_{ad} \\
V_{aq} &= p\lambda_{aq} + p\theta\lambda_{ad} + R_a I_{aq} \\
V_{ao} &= p\lambda_{ao} + R_a I_{ao} \\
0 &= p\lambda_{sd} - pN\lambda_{sq} + R_s I_{sd} \\
0 &= p\lambda_{sq} + pN\lambda_{sd} + R_s I_{sq} \\
0 &= p\lambda_{so} + R_s I_{so} \\
0 &= p\lambda_{rd} + R_r I_{rd} \\
0 &= p\lambda_{rq} + R_r I_{rq} \\
V_f &= p\lambda_f + R_f I_f
\end{aligned}$$

Equation Set (4)

$$
\begin{bmatrix} \lambda_{ad} \\ \lambda_{aq} \\ \lambda_{ao} \\ \lambda_{sd} \\ \lambda_{sq} \\ \lambda_{so} \\ \lambda_{rd} \\ \lambda_{rq} \\ \lambda_{f} \end{bmatrix}
=
\begin{bmatrix}
L_a - M_{aa} & 0 & 0 & \frac{3}{2}M_{as} & 0 & 0 & M_{ar} & 0 & M_{af} \\
0 & L_a - M_{aa} & 0 & 0 & \frac{3}{2}M_{as} & 0 & 0 & M_{ar} & 0 \\
0 & 0 & L_a + 2M_{aa} & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{3}{2}M_{as} & 0 & 0 & L_s - M_{ss} & 0 & 0 & M_{sr} & 0 & M_{sf} \\
0 & \frac{3}{2}M_{as} & 0 & 0 & L_s - M_{ss} & 0 & 0 & M_{sr} & 0 \\
0 & 0 & 0 & 0 & 0 & L_s + 2M_{ss} & 0 & 0 & 0 \\
\frac{3}{2}M_{ar} & 0 & 0 & \frac{3}{2}M_{sr} & 0 & 0 & L_r & 0 & M_{rf} \\
0 & \frac{3}{2}M_{ar} & 0 & 0 & \frac{3}{2}M_{sr} & 0 & 0 & L_r & 0 \\
\frac{3}{2}M_{af} & 0 & 0 & \frac{3}{2}M_{sf} & 0 & 0 & M_{rf} & 0 & L_f
\end{bmatrix}
\begin{bmatrix} I_{ad} \\ I_{aq} \\ I_{ao} \\ I_{sd} \\ I_{sq} \\ I_{so} \\ I_{rd} \\ I_{rq} \\ I_{f} \end{bmatrix}
$$

Equation Set (5)

$$
\begin{bmatrix} V_{ad} \\ V_{aq} \\ V_{ao} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ V_f \end{bmatrix}
=
\begin{bmatrix}
R_a + p(L_a - M_{aa}) & -p\theta(L_a - M_{aa}) & 0 & \frac{3}{2}pM_{as} & -\frac{3}{2}p\theta M_{as} & 0 & pM_{ar} & -p\theta M_{ar} & pM_{af} \\
p\theta(L_a - M_{aa}) & R_a + p(L_a - M_{aa}) & 0 & \frac{3}{2}p\theta M_{as} & \frac{3}{2}pM_{as} & 0 & p\theta M_{ar} & pM_{ar} & p\theta M_{af} \\
0 & 0 & R_a + p(L_a + 2M_{aa}) & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{3}{2}pM_{as} & -\frac{3}{2}pNM_{as} & 0 & R_s + p(L_s - M_{ss}) & pN(L_s - M_{ss}) & 0 & pM_{sr} & -pNM_{sr} & pM_{sf} \\
\frac{3}{2}pNM_{as} & \frac{3}{2}pM_{as} & 0 & pN(L_s - M_{ss}) & R_s + p(L_s - M_{ss}) & 0 & pNM_{sr} & pM_{sr} & pNM_{sf} \\
0 & 0 & 0 & 0 & 0 & R_s + p(L_s + 2M_{ss}) & 0 & 0 & 0 \\
\frac{3}{2}pM_{ar} & 0 & 0 & \frac{3}{2}pM_{sr} & 0 & 0 & R_r + pL_r & 0 & pM_{rf} \\
0 & \frac{3}{2}pM_{ar} & 0 & 0 & \frac{3}{2}M_{sr} & 0 & 0 & R_r + pL_r & 0 \\
\frac{3}{2}pM_{af} & 0 & 0 & \frac{3}{2}pM_{sf} & 0 & 0 & pM_{sf} & 0 & R_f + pL_f
\end{bmatrix}
\begin{bmatrix} I_{ad} \\ I_{aq} \\ I_{ao} \\ I_{sd} \\ I_{sq} \\ I_{so} \\ I_{rd} \\ I_{rq} \\ I_f \end{bmatrix}
$$

Equation Set (6)

Equation set (4) can now be obtained directly from equation sets (5) and (6).

A further simplification may be made to equation set (5) by per unitizing it in accordance with reference (3). First, equation set (5) is re-written as equation sets (7), (8) and (9).

Then, the ordinary variables in equation sets (7), (8) and (9) are normalized in accordance with reference (3) by dividing each variable quantity by a corresponding base quantity. The results are shown as equation sets (10), (11) and (12).

It is highly desirable that the resulting per-unitized mutual inductances exhibit the property of reciprocity, that is $M_{ij} = M_{ji}$. This imposes the following restrictions on the base quantity selection.

$$\frac{3}{2} V_{ab} I_{ab} = \frac{3}{2} V_{sb} I_{sb} = V_{rb} I_{rb} = V_{fb} I_{fb}$$

Additionally, the following conditions on the base quantities are arbitrarily imposed to simplify the per-unitized equations.

$$X_a = \frac{3}{2} \frac{M_{as} W_o I_{sb}}{V_{ab}} = 3 \frac{M_{ar} W_o I_{rb}}{V_{ab}} = \frac{M_{af} W_o I_{fb}}{V_{ab}} = \frac{(L_a - M_{aa}) W_o I_{ab}}{V_{ab}}$$

Thus, at this point, six constraints have been placed on the eight base quantities. This leaves only two base quantity parameters free to be chosen arbitrarily. Once these two more conditions are specified the base quantities will be completely determined. Further consideration of base quantities is given in appendix (H).

Equation sets (10), (11) and (12) may now be written as equations sets (13), (14) and (15).

$$\begin{bmatrix} \lambda_{ad} \\ \lambda_{sd} \\ \lambda_{rd} \\ \lambda_{f} \end{bmatrix} = \begin{bmatrix} L_a - M_{aa} & \frac{3}{2}M_{as} & M_{ar} & M_{af} \\ \frac{3}{2}M_{as} & L_s - M_{ss} & M_{sr} & M_{sf} \\ \frac{3}{2}M_{ar} & \frac{3}{2}M_{sr} & L_r & M_{rf} \\ \frac{3}{2}M_{af} & \frac{3}{2}M_{sf} & M_{rf} & L_f \end{bmatrix} \begin{bmatrix} I_{ad} \\ I_{sd} \\ I_{rd} \\ I_{f} \end{bmatrix}$$

Equation Set (7)

$$\begin{bmatrix} \lambda_{aq} \\ \lambda_{sq} \\ \lambda_{rq} \end{bmatrix} = \begin{bmatrix} L_a - M_{aa} & \frac{3}{2}M_{as} & M_{ar} \\ \frac{3}{2}M_{as} & L_a - M_{ss} & M_{sr} \\ \frac{3}{2}M_{ar} & \frac{3}{2}M_{sr} & L_r \end{bmatrix} \begin{bmatrix} I_{aq} \\ I_{sq} \\ I_{rq} \end{bmatrix}$$

Equation Set (8)

$$\begin{bmatrix} \lambda_{ao} \\ \lambda_{so} \end{bmatrix} = \begin{bmatrix} L_a + 2M_{aa} & 0 \\ 0 & L_s + 2M_{ss} \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{so} \end{bmatrix}$$

Equation Set (9)

$$
\begin{bmatrix} \dfrac{W_o\lambda_{ad}}{V_{ab}} \\[2ex] \dfrac{W_o\lambda_{sd}}{V_{sb}} \\[2ex] \dfrac{W_o\lambda_{rd}}{V_{rb}} \\[2ex] \dfrac{W_o\lambda_{f}}{V_{fb}} \end{bmatrix} = \begin{bmatrix} \dfrac{(L_a-M_{aa})W_oI_{ab}}{V_{ab}} & \dfrac{3}{2}\dfrac{M_{as}W_oI_{sb}}{V_{ab}} & \dfrac{M_{ar}W_oI_{rb}}{V_{ab}} & \dfrac{M_{af}W_oI_{fb}}{V_{ab}} \\[2ex] \dfrac{3}{2}\dfrac{M_{as}W_oI_{ab}}{V_{sb}} & \dfrac{(L_s-M_{ss})W_oI_{sb}}{V_{sb}} & \dfrac{M_{sr}W_oI_{rb}}{V_{sb}} & \dfrac{M_{sf}W_oI_{fb}}{V_{sb}} \\[2ex] \dfrac{3}{2}\dfrac{M_{ar}W_oI_{ab}}{V_{rb}} & \dfrac{3}{2}\dfrac{M_{sr}W_oI_{sb}}{V_{rb}} & \dfrac{L_rW_oI_{rb}}{V_{rb}} & \dfrac{M_{rf}W_oI_{fb}}{V_{rb}} \\[2ex] \dfrac{3}{2}\dfrac{M_{af}W_oI_{ab}}{V_{fb}} & \dfrac{3}{2}\dfrac{M_{sf}W_oI_{sb}}{V_{fb}} & \dfrac{M_{rf}W_oI_{rb}}{V_{fb}} & \dfrac{L_fW_oI_{fb}}{V_{fb}} \end{bmatrix} \begin{bmatrix} \dfrac{I_{ad}}{I_{ab}} \\[2ex] \dfrac{I_{sd}}{I_{sb}} \\[2ex] \dfrac{I_{rd}}{I_{rb}} \\[2ex] \dfrac{I_{f}}{I_{fb}} \end{bmatrix}
$$

Equation Set (10)

$$
\begin{bmatrix} \dfrac{W_o\lambda_{aq}}{V_{ab}} \\[2ex] \dfrac{W_o\lambda_{sq}}{V_{sb}} \\[2ex] \dfrac{W_o\lambda_{rq}}{V_{rb}} \end{bmatrix} = \begin{bmatrix} \dfrac{(L_a-M_{aa})W_oI_{ab}}{V_{ab}} & \dfrac{3}{2}\dfrac{M_{as}W_oI_{sb}}{V_{ab}} & \dfrac{M_{ar}W_oI_{rb}}{V_{ab}} \\[2ex] \dfrac{3}{2}\dfrac{M_{as}W_oI_{ab}}{V_{sb}} & \dfrac{(L_s-M_{ss})W_oI_{sb}}{V_{sb}} & \dfrac{M_{sr}W_oI_{rb}}{V_{sb}} \\[2ex] \dfrac{3}{2}\dfrac{M_{ar}W_oI_{ab}}{V_{rb}} & \dfrac{3}{2}\dfrac{M_{sr}W_oI_{sb}}{V_{rb}} & \dfrac{L_rW_oI_{rb}}{V_{rb}} \end{bmatrix} \begin{bmatrix} \dfrac{I_{aq}}{I_{ab}} \\[2ex] \dfrac{I_{aq}}{I_{sb}} \\[2ex] \dfrac{I_{rq}}{I_{rb}} \end{bmatrix}
$$

Equation Set (11)

$$
\begin{bmatrix} \dfrac{W_o\lambda_{ao}}{V_{ab}} \\[2ex] \dfrac{W_o\lambda_{ao}}{V_{sb}} \end{bmatrix} = \begin{bmatrix} \dfrac{(L_a+2M_{ao})W_oI_{ab}}{V_{ab}} & 0 \\[2ex] 0 & \dfrac{(L_s+2M_{ss})W_oI_{sb}}{V_{sb}} \end{bmatrix} \begin{bmatrix} \dfrac{I_{ao}}{I_{ab}} \\[2ex] \dfrac{I_{so}}{I_{sb}} \end{bmatrix}
$$

Equation Set (12)

$$\begin{bmatrix} \Psi_{ad} \\ \Psi_{sd} \\ \Psi_{rd} \\ \Psi_{f} \end{bmatrix} = \begin{bmatrix} X_a & X_a & X_a & X_a \\ X_a & X_s & X_{sr} & X_{sf} \\ X_a & X_{sr} & X_r & X_{rf} \\ X_a & X_{sf} & X_{rf} & X_f \end{bmatrix} \begin{bmatrix} I_{adp} \\ I_{sdp} \\ I_{rdp} \\ I_{fp} \end{bmatrix}$$

Equation Set (13)

$$\begin{bmatrix} \Psi_{aq} \\ \Psi_{sq} \\ \Psi_{rq} \end{bmatrix} = \begin{bmatrix} X_a & X_a & X_a \\ X_a & X_s & X_{sr} \\ X_a & X_{sr} & X_r \end{bmatrix} \begin{bmatrix} I_{aqp} \\ I_{sqp} \\ I_{rqp} \end{bmatrix}$$

Equation Set (14)

$$\begin{bmatrix} \Psi_{ao} \\ \Psi_{so} \end{bmatrix} = \begin{bmatrix} X_{ao} & 0 \\ 0 & X_{so} \end{bmatrix} \begin{bmatrix} I_{aop} \\ I_{sop} \end{bmatrix}$$

Equation Set (15)

$$\begin{bmatrix} \Psi_{ad} \\ \Psi_{sd} \\ \Psi_{rd} \\ \Psi_{f} \end{bmatrix} = \begin{bmatrix} X_a & X_a & X_a & X_a \\ X_a & X_s & X_s & X_s \\ X_a & X_s & X_r & X_r \\ X_a & X_s & X_r & X_f \end{bmatrix} \begin{bmatrix} I_{adp} \\ I_{sdp} \\ I_{rdp} \\ I_{fp} \end{bmatrix}$$

Equation Set (16)

$$\begin{bmatrix} \Psi_{aq} \\ \Psi_{sq} \\ \Psi_{rq} \end{bmatrix} = \begin{bmatrix} X_a & X_a & X_a \\ X_a & X_s & X_s \\ X_a & X_s & X_r \end{bmatrix} \begin{bmatrix} I_{aqp} \\ I_{sqp} \\ I_{rqp} \end{bmatrix}$$

Equation Set (17)

$$\begin{bmatrix} \Psi_{ao} \\ \Psi_{so} \end{bmatrix} = \begin{bmatrix} X_{ao} & 0 \\ 0 & X_{so} \end{bmatrix} \begin{bmatrix} I_{aop} \\ I_{sop} \end{bmatrix}$$

Equation Set (18)

Appendix (A) shows that $X_s = X_{sr} = X_{sf}$ and $X_r = X_{rf}$ so equation sets (13), (14) and (15) can be re-written as equation sets (16), (17) and (18) respectively.

If the base quantities utilized to obtain equation sets (10), (11) and (12) are applied to equation set (4), equation set (19) results.

Now, if equation set (19) is solved for the time derivatives of the fluxes, equation set (20) results.

Equation sets (16), (17) and (18) can be inverted so that fluxes are the dependent variables and currents are the independent variables. The resulting equations are shown as equation sets (21), (22) and (23); where,

$$X_j = \frac{X_s (X_s - X_r)}{X_a (X_a - X_s)}$$

$$X_k = \frac{(X_s - X_r)}{(X_a - X_s)}$$

$$X_l = \frac{(X_a - X_r)}{(X_a - X_s)}$$

$$X_m = \frac{(X_s - X_r)}{(X_r - X_f)}$$

$$X_o = \frac{W_o}{(X_r - X_s)}$$

Equation sets (21), (22), (23) and (20) can be combined to obtain equation set (24).

The direct and quadrature axis voltages of the stator armature are given by: $V_{adp} = V_a \cos (\theta)$ and $V_{aqp} = - V_a \sin (\theta)$

$$V_{adp} = \frac{p}{W_o}\Psi_{ad} - \frac{(p\theta)}{W_o}\Psi_{aq} + R_{ap}\, I_{adp}$$

$$V_{aqp} = \frac{p}{W_o}\Psi_{aq} + \frac{(p\theta)}{W_o}\Psi_{ad} + R_{ap}\, I_{aqp}$$

$$V_{aop} = \frac{p}{W_o}\Psi_{ao} + R_{ap}\, I_{aop}$$

$$0 = \frac{p}{W_o}\Psi_{sd} - \frac{(pN)}{W_o}\Psi_{sq} + R_{sp}\, I_{sdp}$$

$$0 = \frac{p}{W_o}\Psi_{sq} + \frac{(pN)}{W_o}\Psi_{sd} + R_{sp}\, I_{sq}$$

$$0 = \frac{p}{W_o}\Psi_{so} + R_{sp}\, I_{sop}$$

$$0 = \frac{p}{W_o}\Psi_{rd} + R_{rp}\, I_{rdp}$$

$$0 = \frac{p}{W_o}\Psi_{rq} + R_{rp}\, I_{rqp}$$

$$V_{fp} = \frac{p}{W_o}\Psi_{f} + R_{fp}\, I_{fp}$$

Equation Set (19)

$$p\Psi_{ad} = W_o V_{adp} + (p\theta)\Psi_{aq} - W_o R_{ap} I_{adp}$$

$$p\Psi_{aq} = W_o V_{aqp} + (p\theta)\Psi_{ad} - W_o R_{ap} I_{aqp}$$

$$p\Psi_{ao} = W_o V_{aop} - W_o R_{ap} I_{aop}$$

$$p\Psi_{sd} = (p\theta)\Psi_{sq} - W_o R_{sp} I_{sdp}$$

$$p\Psi_{sq} = (pN)\Psi_{sd} - W_o R_{sp} I_{sqp}$$

$$p\Psi_{so} = - W_o R_{sp} I_{sop}$$

$$p\Psi_{rd} = - W_o R_{rp} I_{rdp}$$

$$p\Psi_{rq} = - W_o R_{rp} I_{rqp}$$

$$p\Psi_{f} = W_o V_{fp} - W_o R_{fp} I_{fp}$$

Equation Set (20)

$$\begin{bmatrix} I_{adp} \\ I_{sdp} \\ I_{rdp} \\ I_{fp} \end{bmatrix} = \frac{X_o}{W_o} \begin{bmatrix} X_j & -X_k & 0 & 0 \\ -X_k & X_l & -1 & 0 \\ 0 & -1 & (1+X_m) & -X_m \\ 0 & 0 & -X_m & X_m \end{bmatrix} \begin{bmatrix} \Psi_{ad} \\ \Psi_{sd} \\ \Psi_{rd} \\ \Psi_{f} \end{bmatrix}$$

Equation Set (21)

$$\begin{bmatrix} I_{aqp} \\ I_{sqp} \\ I_{rqp} \end{bmatrix} = \frac{X_o}{W_o} \begin{bmatrix} X_j & -X_k & 0 \\ -X_k & X_l & -1 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} \Psi_{aq} \\ \Psi_{sq} \\ \Psi_{rq} \end{bmatrix}$$

Equation Set (22)

$$\begin{bmatrix} I_{aop} \\ I_{sop} \end{bmatrix} = \begin{bmatrix} \frac{1}{X_{ao}} & 0 \\ 0 & \frac{1}{X_{so}} \end{bmatrix} \begin{bmatrix} \Psi_{ao} \\ \Psi_{so} \end{bmatrix}$$

Equation Set (23)

$$p\Psi_{ad} = W_o V_{adp} + (p\theta)\Psi_{aq} + R_{ap} X_o (X_k \Psi_{sd} - X_j \Psi_{ad})$$

$$p\Psi_{aq} = W_o V_{aqp} + (p\theta)\Psi_{ad} + R_{ap} X_o (X_k \Psi_{sq} - X_j \Psi_{aq})$$

$$p\Psi_{ao} = W_o V_{aop} - \frac{W_o R_{ap}}{X_{ao}} \Psi_{ao}$$

$$p\Psi_{sd} = (pN)\Psi_{sq} + R_{sp} X_o (X_k \Psi_{ad} - X_1 \Psi_{sd} + \Psi_{rd})$$

$$p\Psi_{sq} = -(pN)\Psi_{sd} + R_{sp} X_o (X_k \Psi_{aq} - X_1 \Psi_{sq} + \Psi_{rq})$$

$$p\Psi_{rd} = R_{rp} X_o \left[\Psi_{sd} - (1 + X_m)\Psi_{rd} + X_m \Psi_f\right]$$

$$p\Psi_{rq} = R_{rp} X_o (\Psi_{sq} - \Psi_{rq})$$

$$p\Psi_{so} = W_o V_{sop} - \frac{W_o R_{ap}}{X_{so}} \Psi_{so}$$

$$p\Psi_f = W_o V_f + R_{fp} X_o X_m (\Psi_{rd} - \Psi_f)$$

Equation Set (24)

The dynamic mechanical equations of the shell and rotor in per unit form are: $p^2(\theta) = W_o\, T_{rp} / 2\, H_r$

and $p^2(\theta - N) = W_o (T_{sp} - T_{lp}) / 2\, H_s$

Appendix (B) provides the following expressions:

$$T_{rp} = \frac{X_o}{W_o} (\Psi_{rd}\, \Psi_{sq} - \Psi_{sd}\, \Psi_{rq})$$

$$T_{sp} = \frac{X_o}{W_o} (\Psi_{sd}\, \Psi_{aq} - \Psi_{ad}\, \Psi_{sq}) - T_{rp}$$

These equations along with the equations of equation set (24) form a complete set of differential equations that mathematically describe the motor's model. It is assumed in this thesis that all loadings and transient states will be symetrical and balanced. Thus, Ψ_{ao} and Ψ_{so} will be assumed to be zero. Additionally, Ψ_f will be considered a constant. This being the case, the given differential equations reduce to a ninth order non-linear set of differential equations. These equations can be solved once all the constant parameters are known. This solution is rather straight forward for the steady state condition, although a computer minimizes the computational effort. The transient state defies a hand solution. The digital computer can be used to simulate the transient state once a set of initial conditions has been determined.

References (8), (9), (10) and (12) provided valuable background material that aided in the development of the equation in this section.

IV Determination of Machine Parameters

The size of the motor is determined in Appendix (C) and the circuit parameters are determined in Appendix (D). The results are summarized in Table (2).

Table 2 Machine Size and Circuit Parameters

Inner Radius of Field	4.0 inches
Outer Radius of Field	6.5 inches
Average Radius of Damper	7.0 inches
Inner Radius of Shell	7.5 inches
Outer Radius of Shell	10.5 inches
Inner Radius of Stator	11.0 inches
Outer Radius of Stator	13.5 inches
Inner Radius of Shield	14.5 inches
Outer Radius of Shield	20.0 inches
Electrical Length	7.4 feet
R_{ap}	0.20
R_{sp}	0.588
R_{rp}	26.87
R_{fp}	0.0 (super-conducting winding)
X_j	7.799
X_k	3.685
X_l	4.685
X_o	10.08
H_s	0.738 seconds
H_r	0.0738 seconds

V Steady State Characteristics

When the motor is running in steady state, the governing differential equations of equation set (24) can be reduced by setting all time derivatives of the fluxes to zero. Additionally, the torque on the rotor must be zero and this directly implies $\Psi_{rq} = \Psi_{sq} = 0$.

Slip, s, is defined defined in the conventional manner; that is,

$$s = \frac{W_r - W_s}{W_r} \qquad \text{where } W_r = p(\theta) = W_o \text{ and } W_s = p(\phi)$$

in the steady state, then $s = \dfrac{W_o - p(\phi)}{W_o}$. As can be seen from figure (3), $\theta = N + \phi$ so $p(N) = W_o - p(\phi)$, so finally $p(N) = s\,W_o$.

Taking equation set (24) and setting the time derivatives of fluxes to zero, letting $\Psi_{sq} = \Psi_{rq} = 0$, and using the relations $pN = s\,W_o$, $p\theta = W_o$ and $I_{fp} = V_{fp} / R_{fp}$, equation set (25) results.

The torque equation of the shell reduces to,

$$T_{sp} = -\frac{X_o}{W_o} \Psi_{sd} \Psi_{aq}$$ and by using the fourth equation of equation set (25), the expression for torque can be written as,

$$T_{sp} = \frac{R_{sp}}{s} \left(\frac{X_o \Psi_{aq}}{W_o} \right)^2$$

Solving for Ψ_{aq} yields $\Psi_{aq} = \dfrac{W_o}{R_{sp}} \sqrt{\dfrac{s\,T_{sp}}{R_{sp}}}$

Assuming that slip, s, stator torque, T_{sp}, and field current, I_f, are the independent variables, then equation set (25) can be solved for the fluxes and voltages which result in equation set (26).

The digital computer is a valuable tool in evaluating the expressions of equations set (26) numerically. Equation set (26) and the machine

$$0 = V_{adp} + \Psi_{aq} + \frac{R_{ap}\, X_o}{W_o} (X_k \Psi_{sd} - X_j \Psi_{ad})$$

$$0 = V_{aqp} - \Psi_{ad} + \frac{R_{ap}\, X_o}{W_o} (- X_j \Psi_{aq})$$

$$0 = X_k \Psi_{ad} - X_1 \Psi_{sd} + \Psi_{rd}$$

$$0 = s \Psi_{sd} + \frac{R_{sp}\, X_o}{W_o} X_k \Psi_{aq}$$

$$0 = \Psi_{sd} - (1 + X_m) \Psi_{rd} + X_m \Psi_f$$

$$0 = I_f + \frac{X_o\, X_m}{W_o} (\Psi_{rd} - \Psi_f)$$

Equation Set (25)

$$\Psi_{aq} = \frac{W_o}{X_o} \sqrt{\frac{s\ T_{sp}}{R_{sp}}}$$

$$\Psi_{ad} = \frac{R_{sp}\ X_o}{s\ W_o} (1 - X_1) \Psi_{aq} + \frac{W_o\ I_f}{X_k\ X_o}$$

$$\Psi_{sq} = 0$$

$$\Psi_{sd} = - \frac{R_{sp}\ X_o}{s\ W_o} \ X_k \Psi_{aq}$$

$$\Psi_{rq} = 0$$

$$\Psi_{rd} = \Psi_{sd} - \frac{W_o\ I_f}{X_o}$$

$$\Psi_f = \Psi_{rd} + \frac{W_o}{X_o\ X_m} I_f$$

$$V_{adp} = - \Psi_{aq} + \frac{R_{ap}\ X_o}{W_o} (X_j \Psi_{ad} - X_k \Psi_{sd})$$

$$V_{aqp} = \Psi_{ad} + \frac{R_{ap}\ X_o}{W_o} X_j \Psi_{aq}$$

$$V_t = \sqrt{(V_{adp})^2 + (V_{aqp})^2}$$

Equation Set (26)

parameters listed in Table (2) along with the load characteristics determined in appendix (E) were injected into an IBM model 370 computer use the WATFIV program listed in appendix (G).

The results of the computer analysis are shown in the results section as figure (4) through (15).

VI Transient State Characteristics

Equation set (24), table (2) and the shell and rotor torque expressions of Appendix (B) provide the mathematical discription of the transient state. Given these equations and a complete set of initial conditions and driving functions, the system is deterministic. The initial conditions are determined in Appendix (F).

The transient state was simulated in four distinct evolutions:

1. Rotor start up with R_{sp} = infinity
2. Shell start up with rotor at full speed and at various values of R_{sp} .
3. Crash back.
4. Three phase fault at the stator armature terminals.

The simulations were all conducted using an IBM model 370 digital computer and the IBM supplied program CSMP (Continuous Systems Modeling Program). The program listings are shown in Appendix (G).

The rotor start up simulation assumed that the shell circuit is open and in effect not there. This was equivalent to starting a conventional single armature machine. The results of this start up ar shown in figure (16).

The shell start up simulation was conducted by first having the rotor running in steady state then placing various values of finite resistance in the shell circuit. The results of this simulation are shown in figure (17).

The crash back simulation first assumed a steady state full power condition for the motor, then the phase sequence of the stator terminal

voltage were reversed. The results of the crash back simulation are shown in figure (18).

The three phase fault simulation again assumes a steady state full power condition for the motor, then the three terminal leads of the stator armature are electrically shorted. In effect $V_{aa} = V_{ab} = V_{ac} = 0$. The results of the three phase fault are shown in figure (19).

VII Results

Figure (4) through figure (15) show the steady state analysis results. In these figures, s, I_{fp} and T_{sp} are the independent variables.

Figures (4), (5) and (6) show the terminal voltages.

Figures (7), (8) and (9) show the terminal currents.

Figures (10), (11) and (12) show the power factor.

Figures (13), (14) and (15) show the rotor angle.

Figure (16) through figure (19) show the angular velocities of the shell in the transient state.

Figure (16) shows the rotor start up transient.

Figure (17) shows the stator start up transient.

Figure (18) shows the crash back transient.

Figure (19) shows the three phase fault transient.

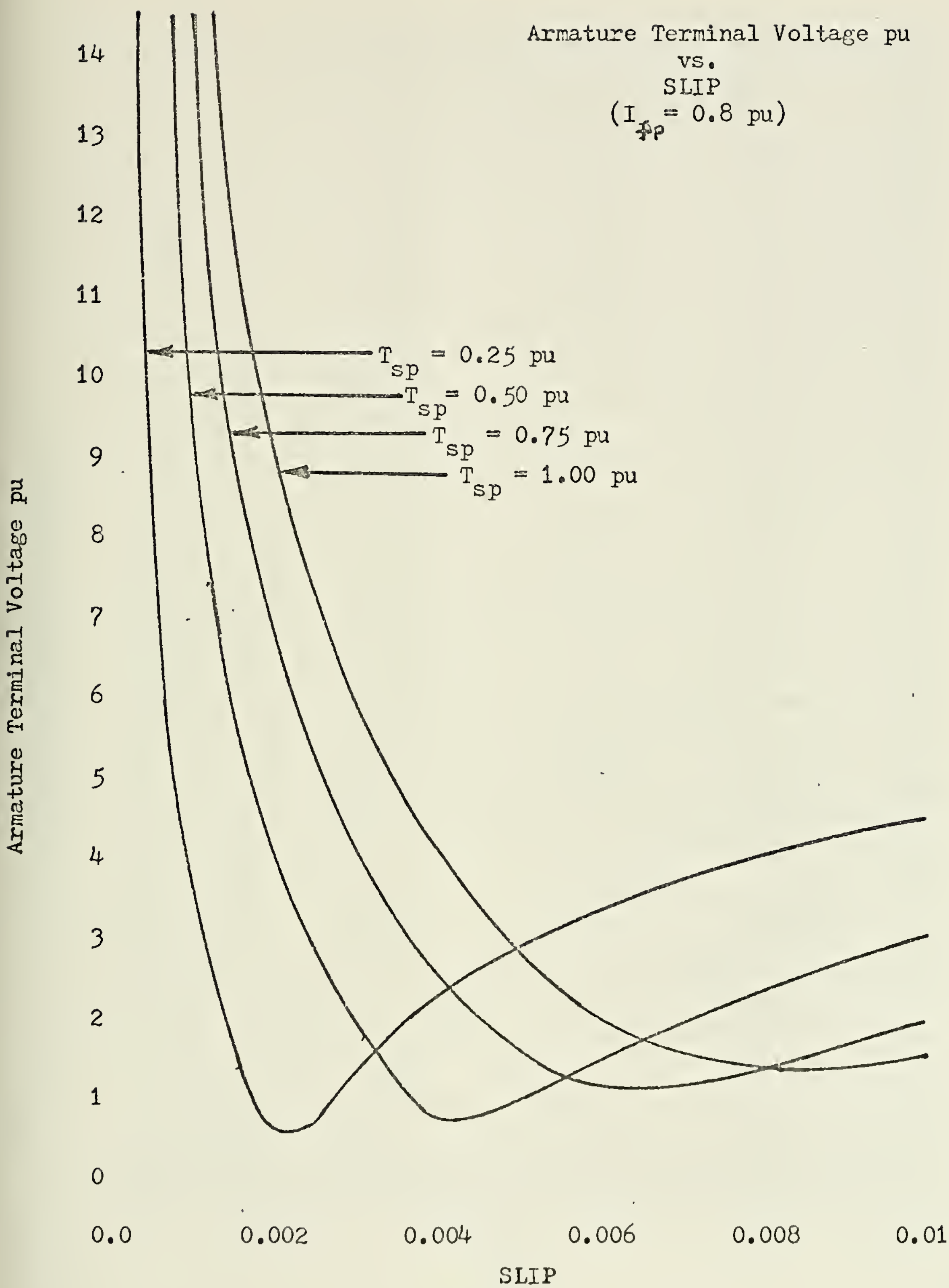

Armature Terminal Voltage pu
vs.
SLIP
(I_{fp} = 0.8 pu)
T_{sp} = 0.25 pu
T_{sp} = 0.50 pu
T_{sp} = 0.75 pu
T_{sp} = 1.00 pu
Armature Terminal Voltage pu
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (4)

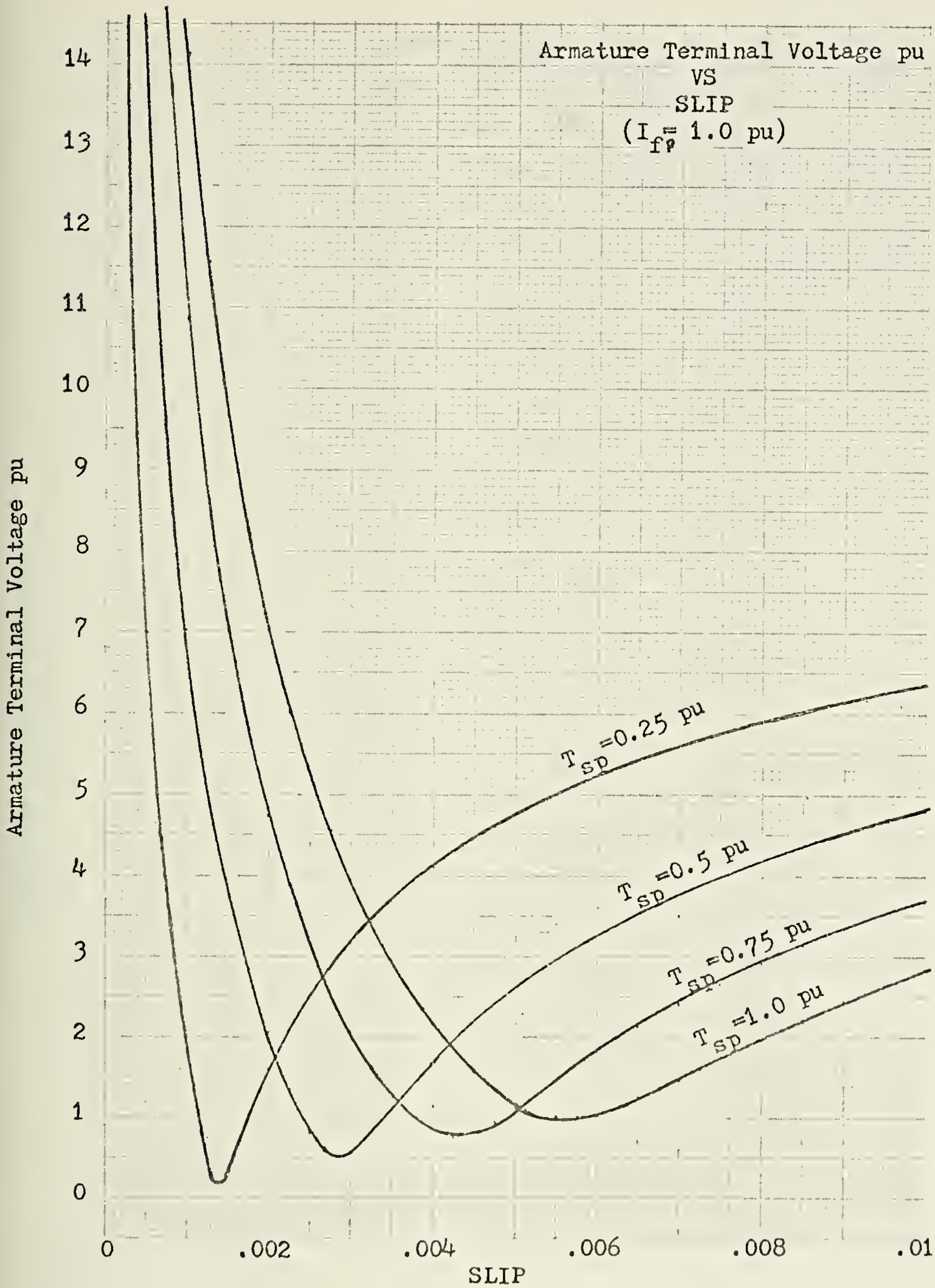
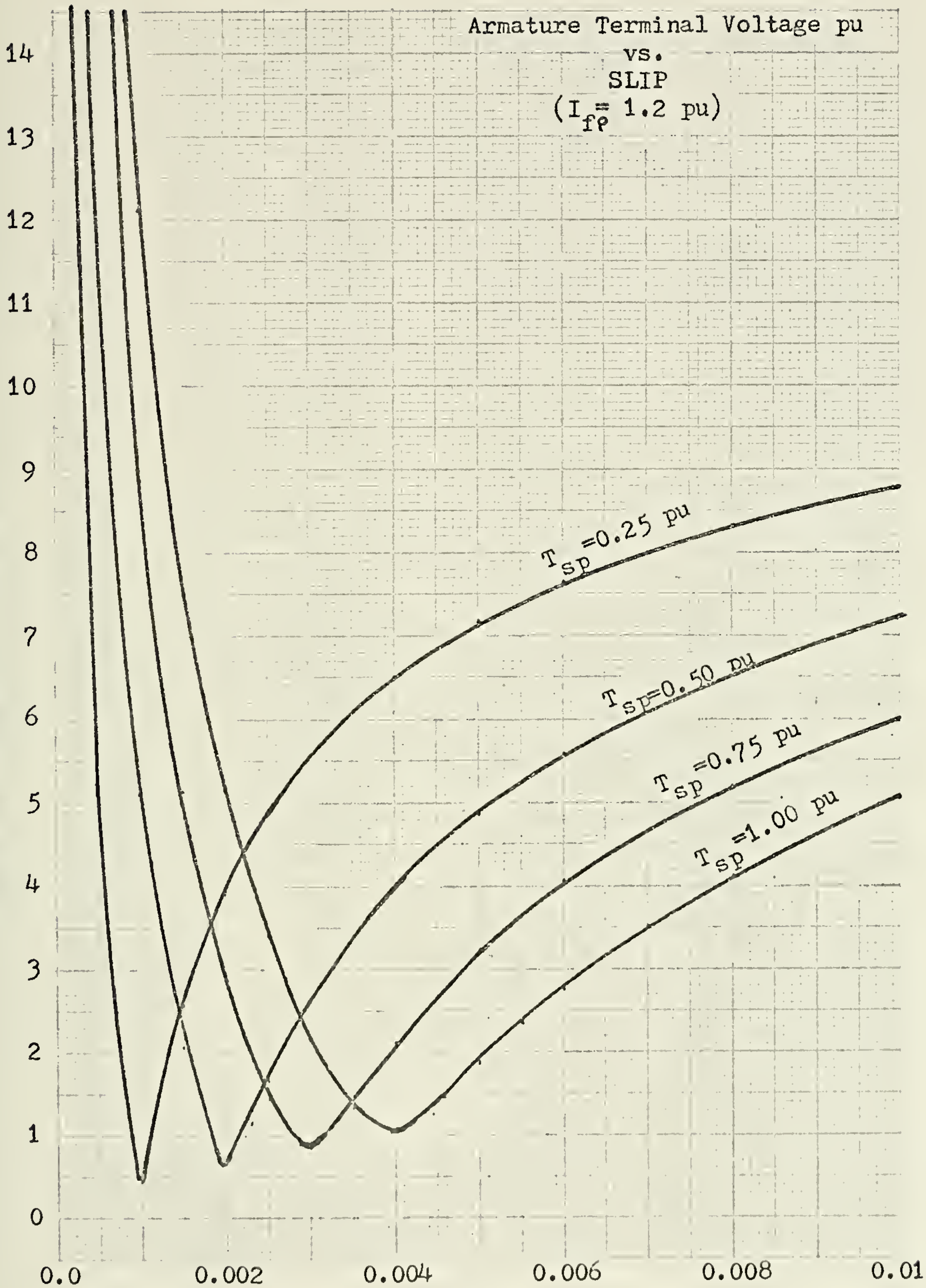

Armature Terminal Voltage pu
VS
SLIP
$(I_{f\varphi} = 1.0$ pu)
T_{sp} =0.25 pu
T_{sp} =0.5 pu
T_{sp} =0.75 pu
T_{sp} =1.0 pu
Armature Terminal Voltage pu
SLIP
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
.002
.004
.006
.008
.01

Figure (5)

Armature Terminal Voltage pu



SLIP

Figure (6)

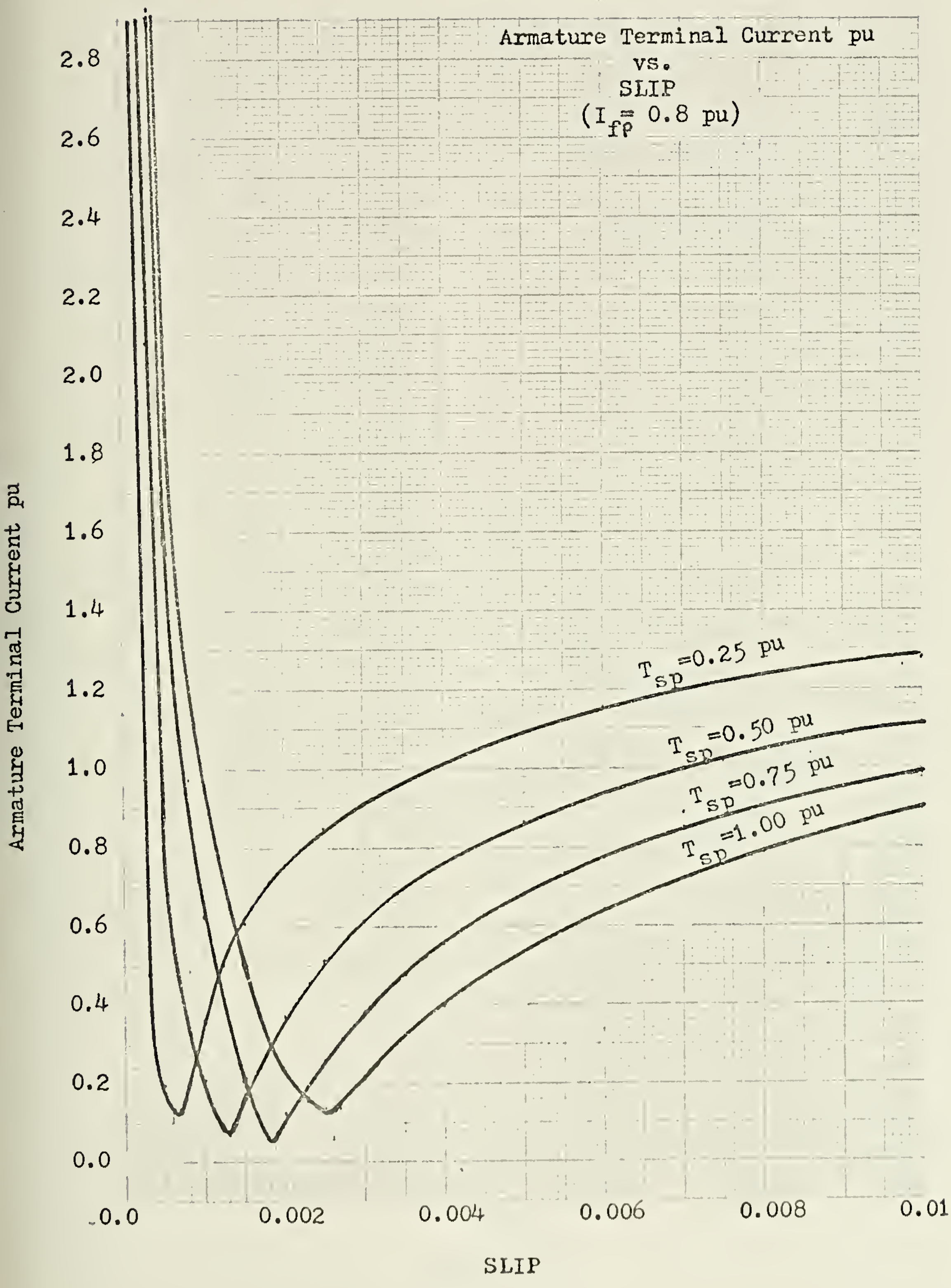

Armature Terminal Current pu
vs.
SLIP
($I_{f\ell}$= 0.8 pu)
T_{sp}=0.25 pu
T_{sp}=0.50 pu
T_{sp}=0.75 pu
T_{sp}=1.00 pu
Armature Terminal Current pu
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (7)

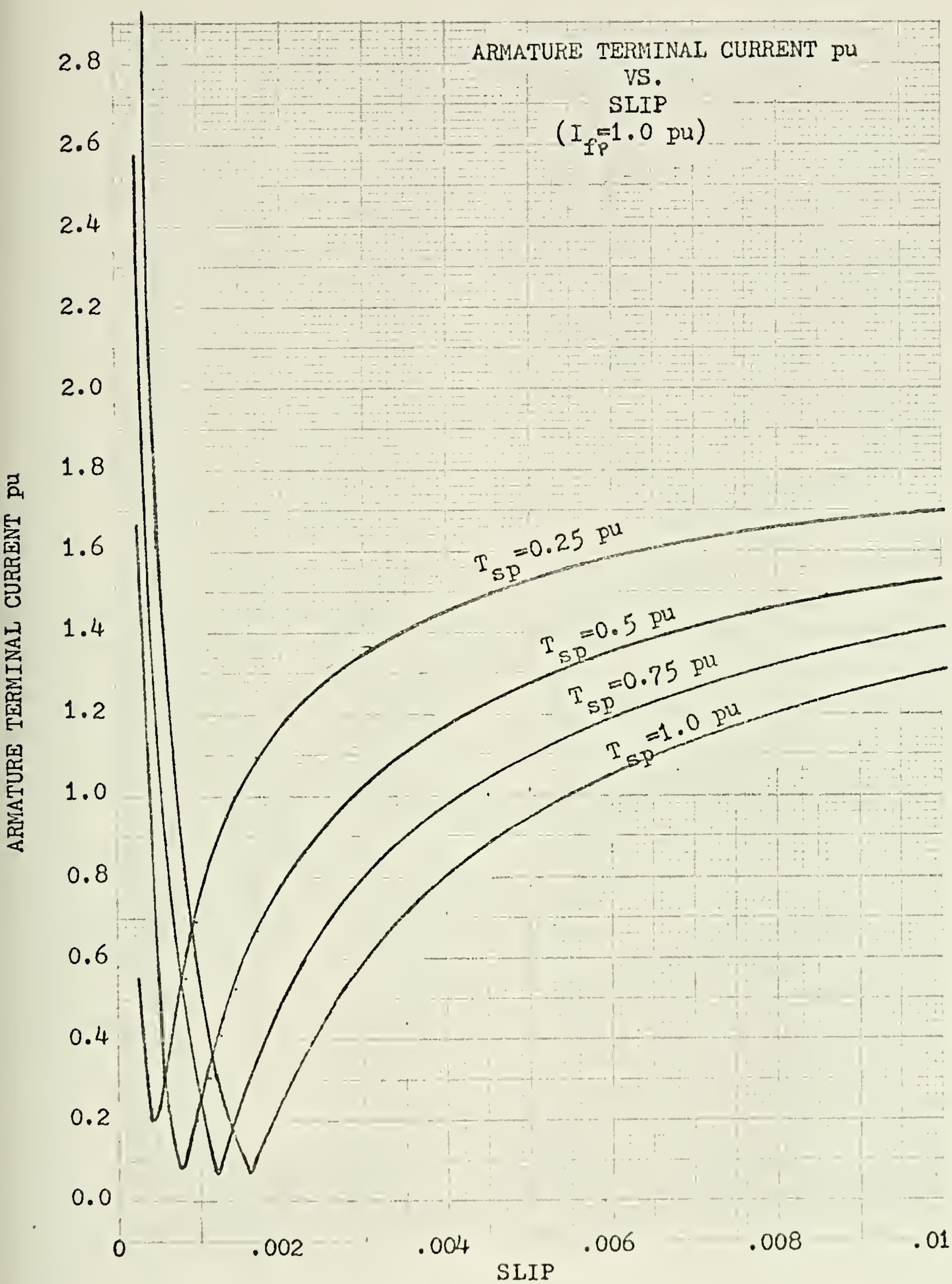
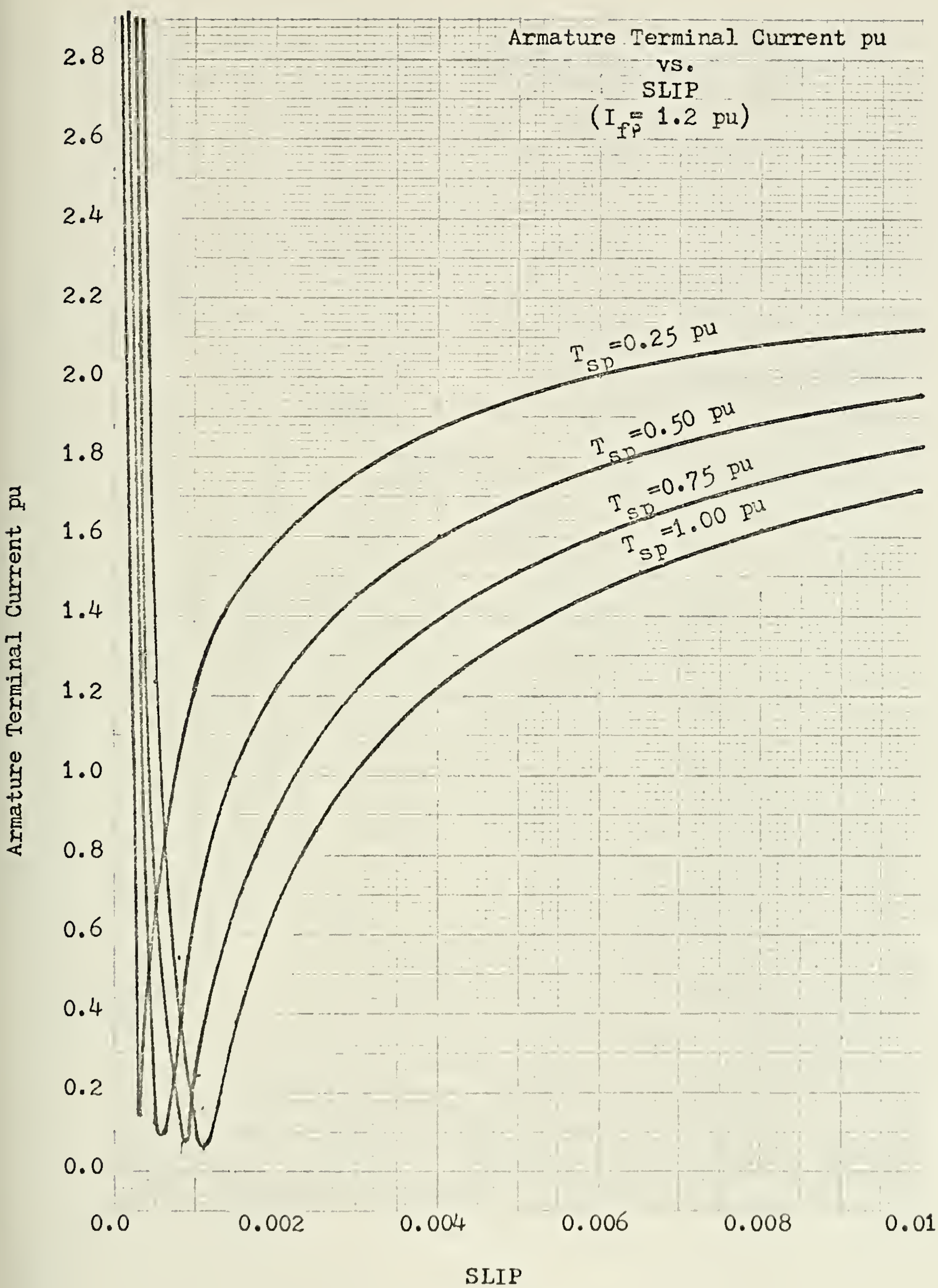

ARMATURE TERMINAL CURRENT pu
VS.
SLIP
(I_{fp}=1.0 pu)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ARMATURE TERMINAL CURRENT pu
T_{sp}=0.25 pu
T_{sp}=0.5 pu
T_{sp}=0.75 pu
T_{sp}=1.0 pu
0
.002
.004
.006
.008
.01
SLIP

Figure (8)



Armature Terminal Current pu
vs.
SLIP
(I_{f}= 1.2 pu)
T_{sp}=0.25 pu
T_{sp}=0.50 pu
T_{sp}=0.75 pu
T_{sp}=1.00 pu
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Armature Terminal Current pu
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (9)

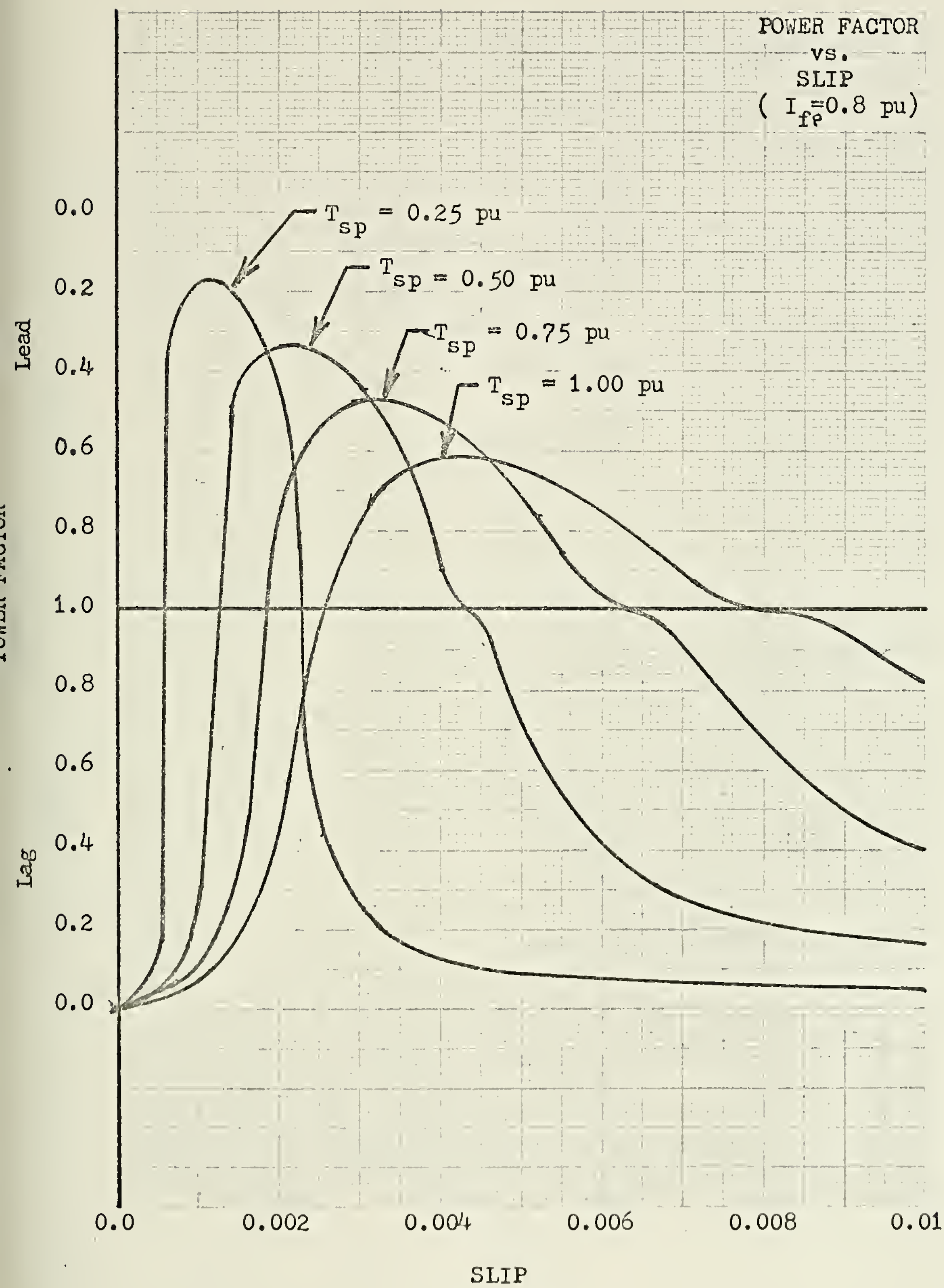

POWER FACTOR
vs.
SLIP
(I_{fe}=0.8 pu)
T_{sp} = 0.25 pu
T_{sp} = 0.50 pu
T_{sp} = 0.75 pu
T_{sp} = 1.00 pu
Lead
Lag
POWER FACTOR
0.0
0.2
0.4
0.6
0.8
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (10)

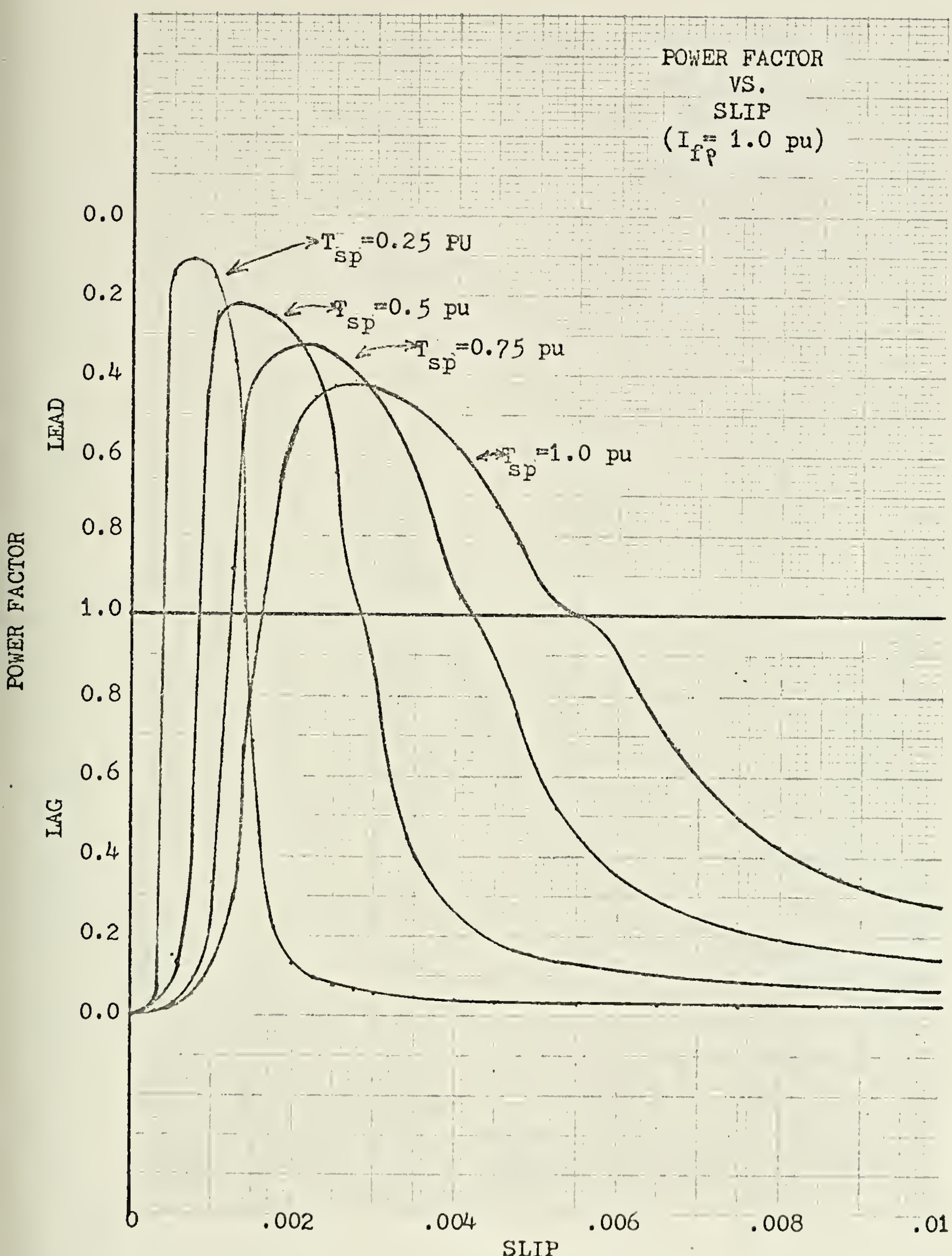

POWER FACTOR
VS.
SLIP
($I_{f\rho}$ = 1.0 pu)
T_{sp}=0.25 PU
T_{sp}=0.5 pu
T_{sp}=0.75 pu
T_{sp}=1.0 pu
POWER FACTOR
LEAD
LAG
0.0
0.2
0.4
0.6
0.8
1.0
0.8
0.6
0.4
0.2
0.0
0
.002
.004
.006
.008
.01
SLIP

Figure (11)

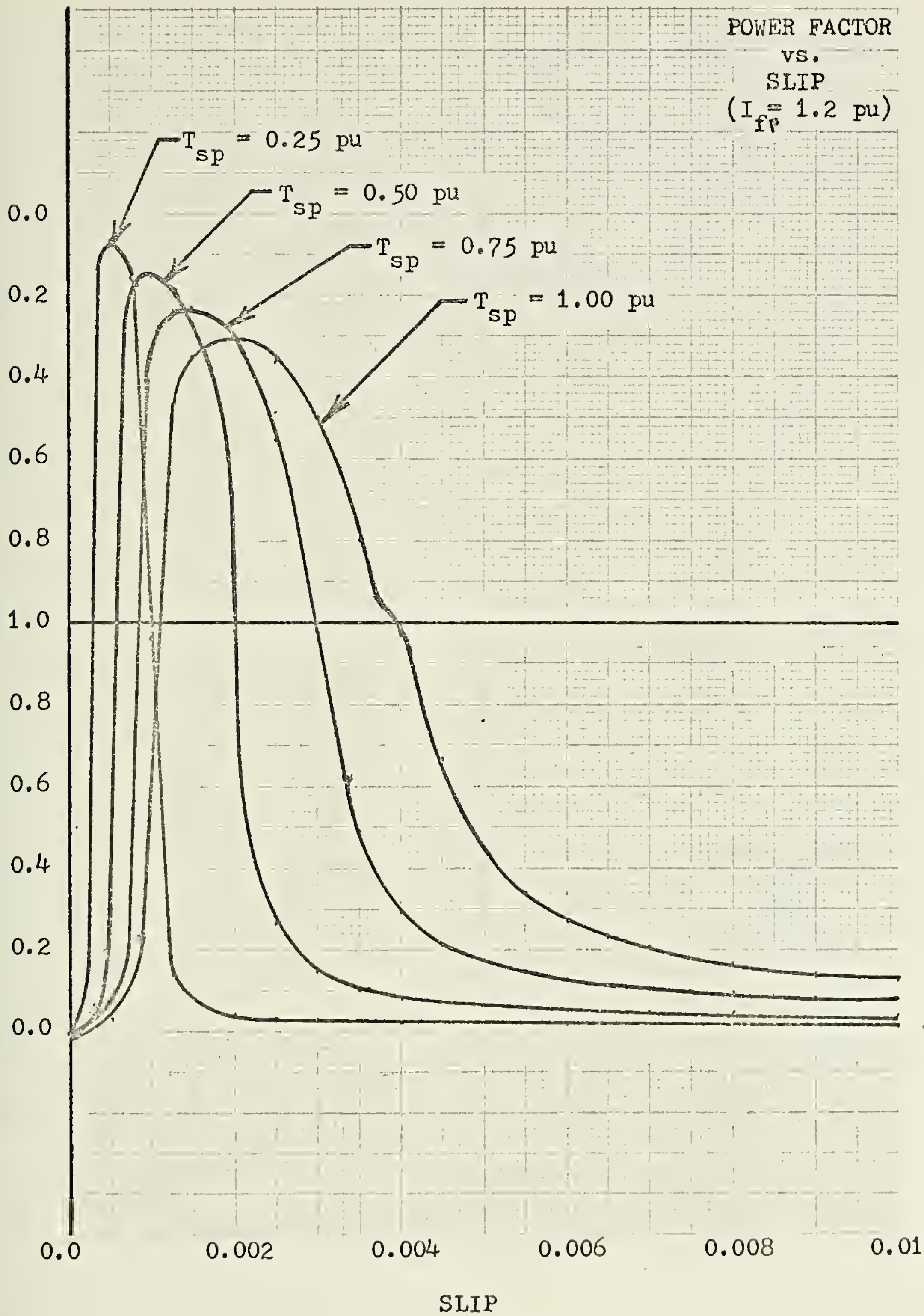

POWER FACTOR
vs.
SLIP
(I_{fr} = 1.2 pu)
T_{sp} = 0.25 pu
T_{sp} = 0.50 pu
T_{sp} = 0.75 pu
T_{sp} = 1.00 pu
0.0
0.2
0.4
0.6
0.8
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (12)

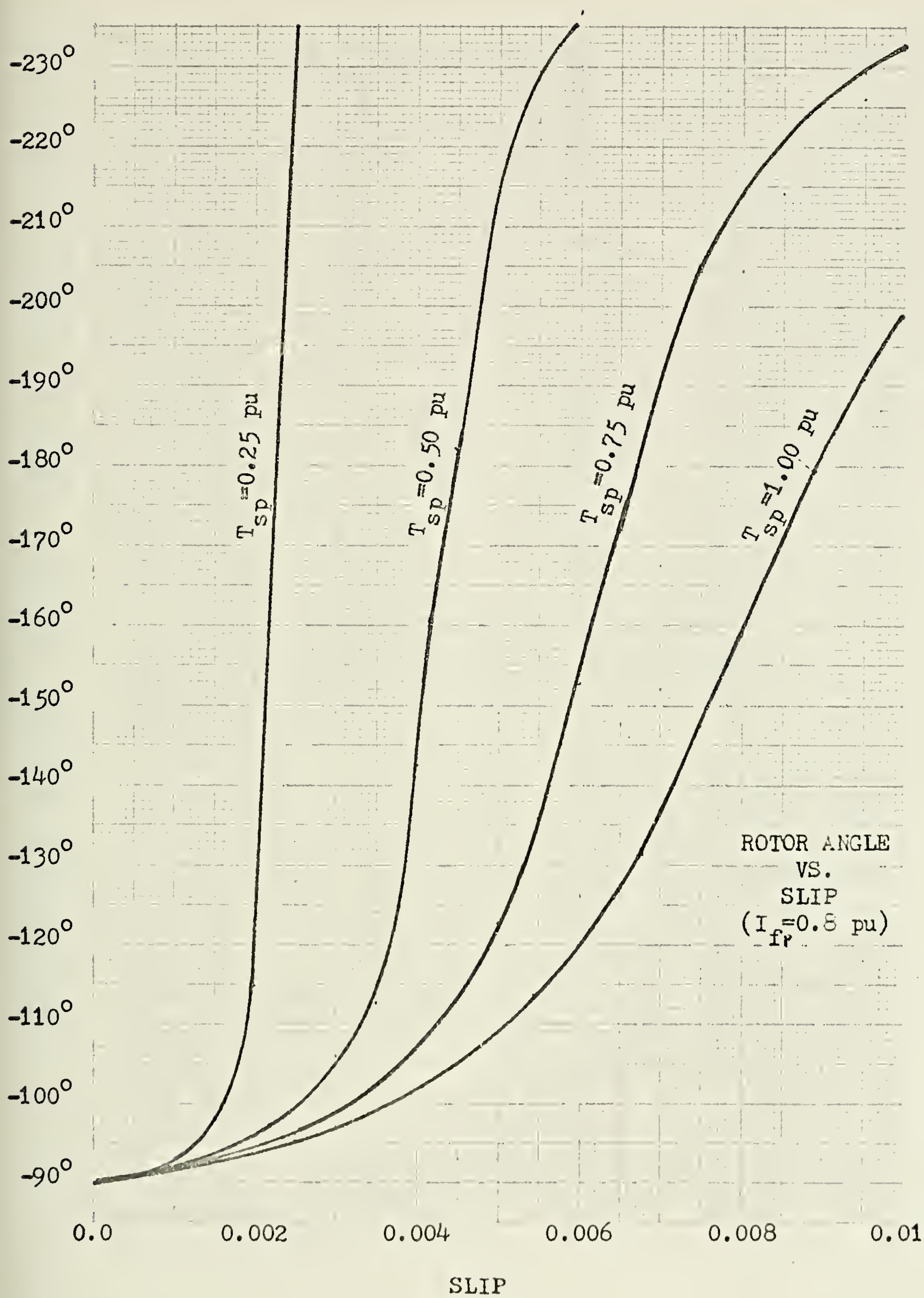

-230°
-220°
-210°
-200°
-190°
-180°
-170°
-160°
-150°
-140°
-130°
-120°
-110°
-100°
-90°
0.0
0.002
0.004
0.006
0.008
0.01
SLIP
T_{sp}=0.25 pu
T_{sp}=0.50 pu
T_{sp}=0.75 pu
T_{sp}=1.00 pu
ROTOR ANGLE
VS.
SLIP
(I_{fr}=0.8 pu)

Figure (13)

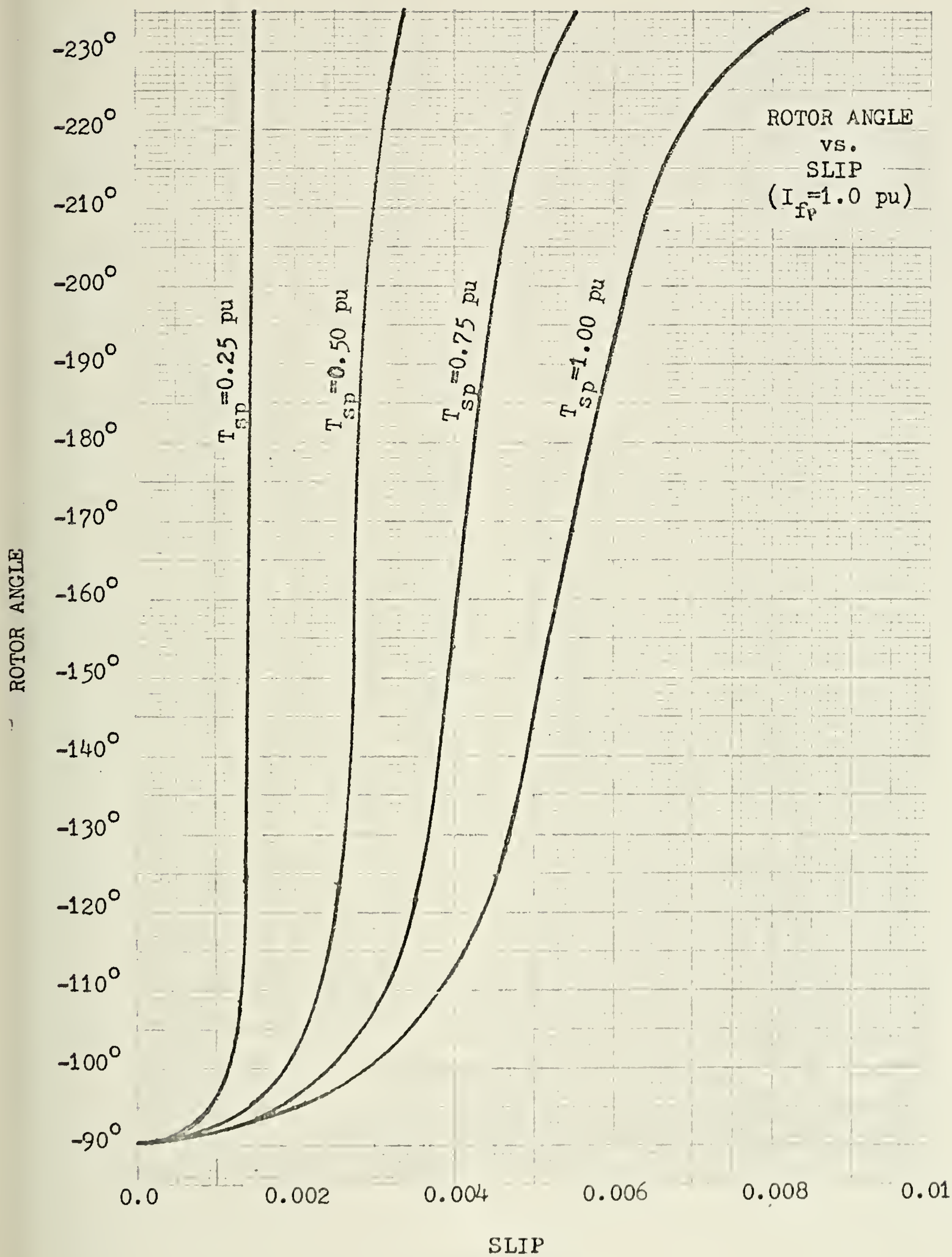

ROTOR ANGLE
vs.
SLIP
(I_{fp}=1.0 pu)
T_{sp}=0.25 pu
T_{sp}=0.50 pu
T_{sp}=0.75 pu
T_{sp}=1.00 pu
-230°
-220°
-210°
-200°
-190°
-180°
-170°
-160°
-150°
-140°
-130°
-120°
-110°
-100°
-90°
ROTOR ANGLE
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (14)

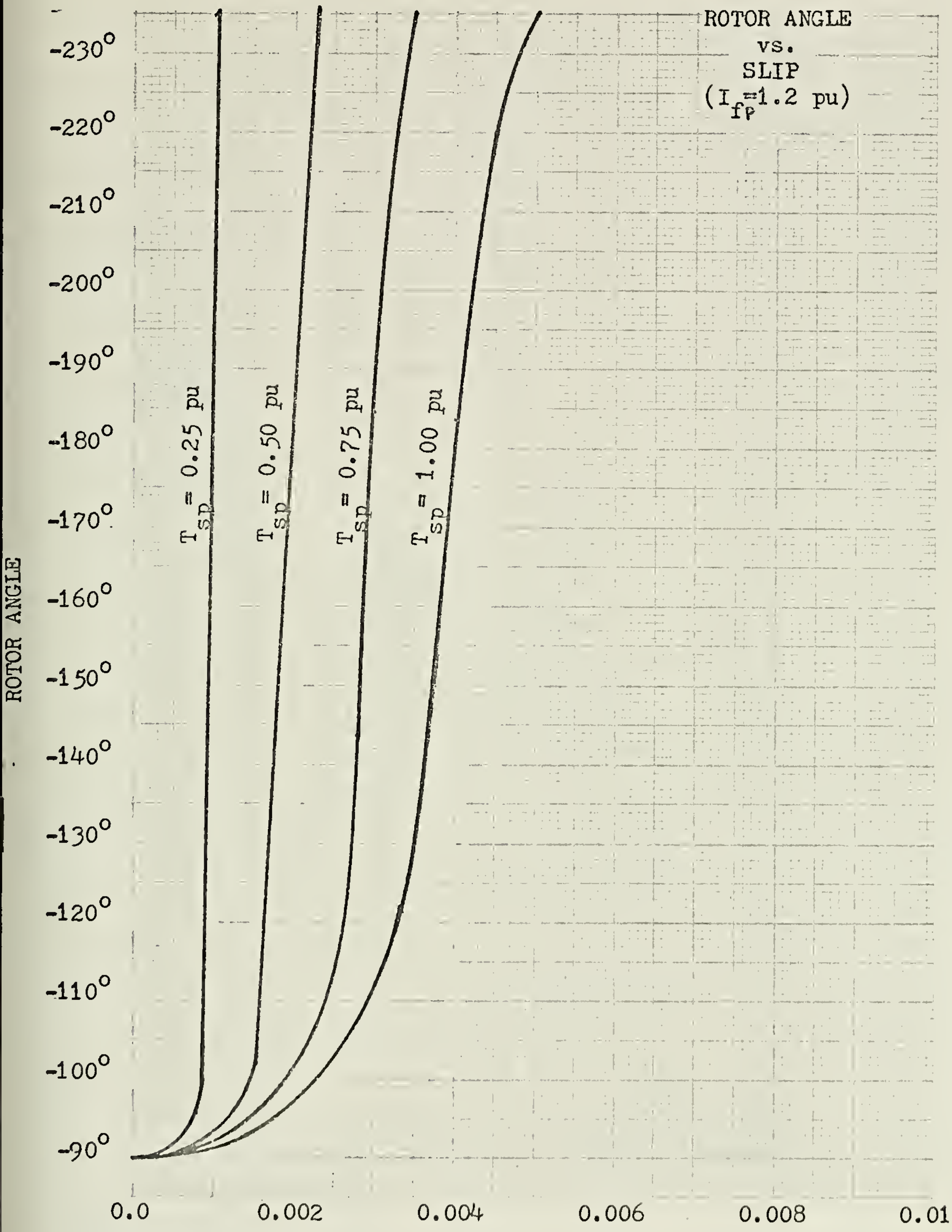

ROTOR ANGLE
vs.
SLIP
(I_{fp}=1.2 pu)
T_{sp} = 0.25 pu
T_{sp} = 0.50 pu
T_{sp} = 0.75 pu
T_{sp} = 1.00 pu
-230°
-220°
-210°
-200°
-190°
-180°
-170°
-160°
-150°
-140°
-130°
-120°
-110°
-100°
-90°
ROTOR ANGLE
0.0
0.002
0.004
0.006
0.008
0.01
SLIP

Figure (15)

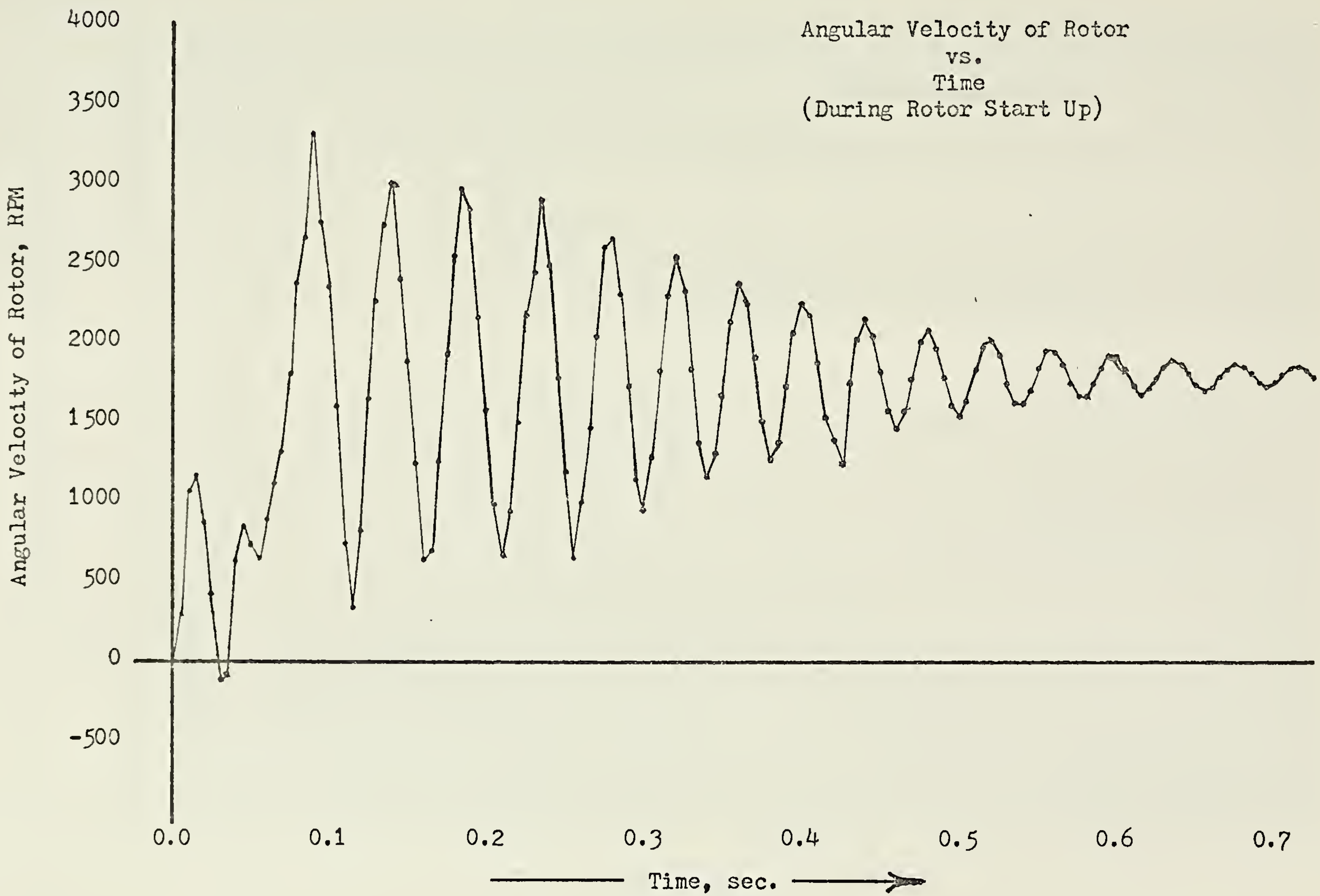
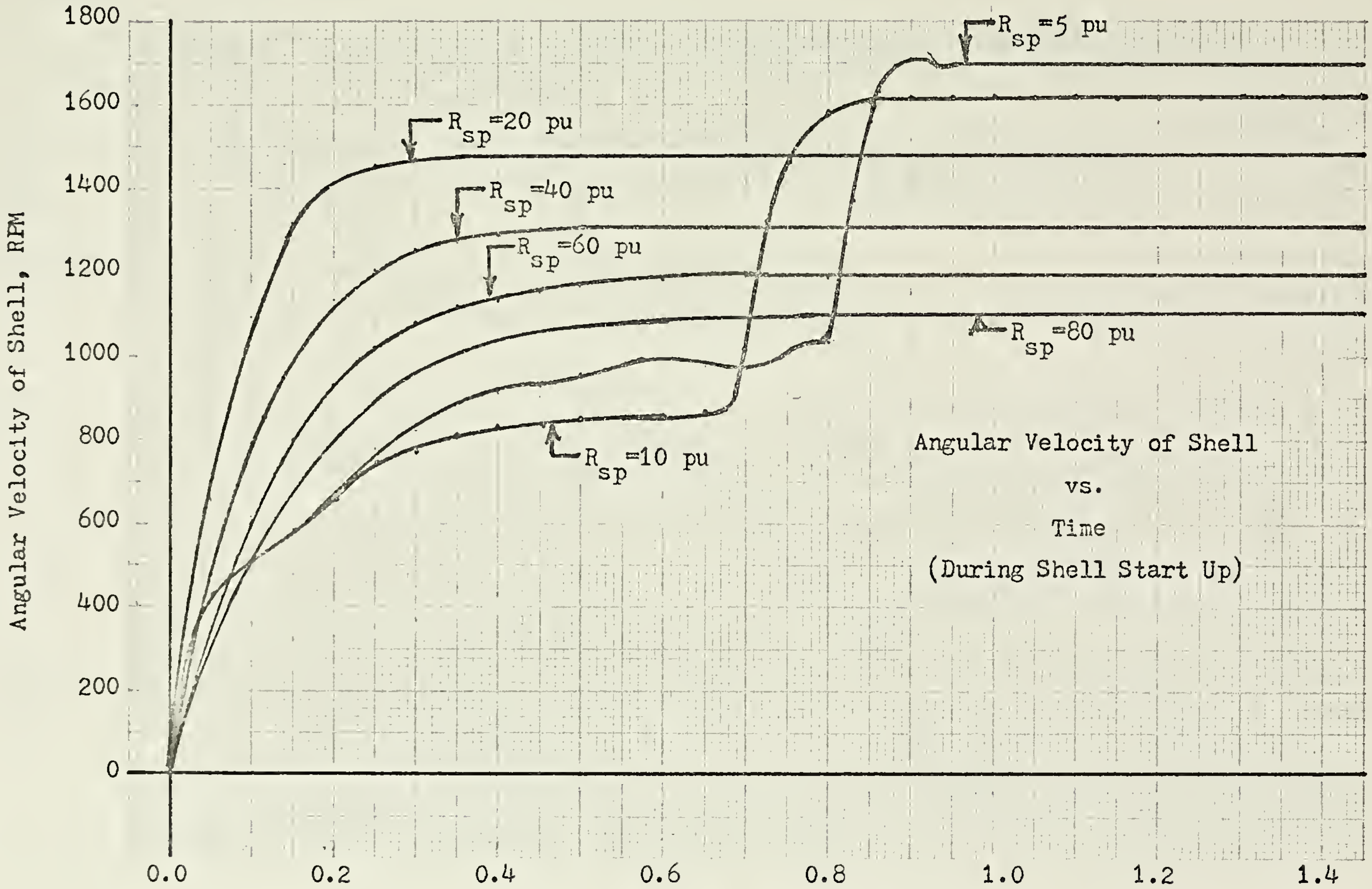
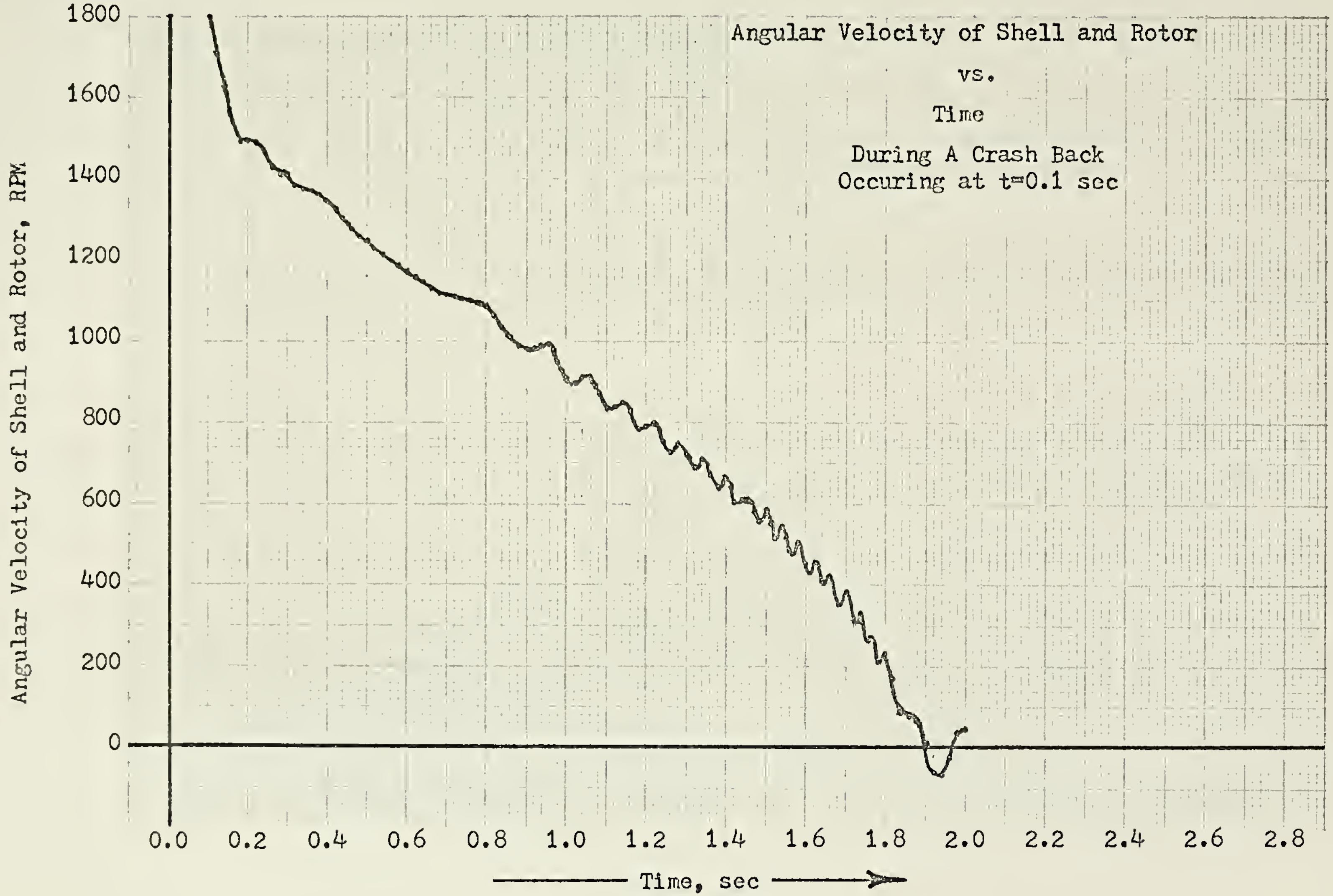

Angular Velocity of Rotor
vs.
Time
(During Rotor Start Up)
Angular Velocity of Rotor, RPM
4000
3500
3000
2500
2000
1500
1000
500
0
-500
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time, sec.

Figure (16)



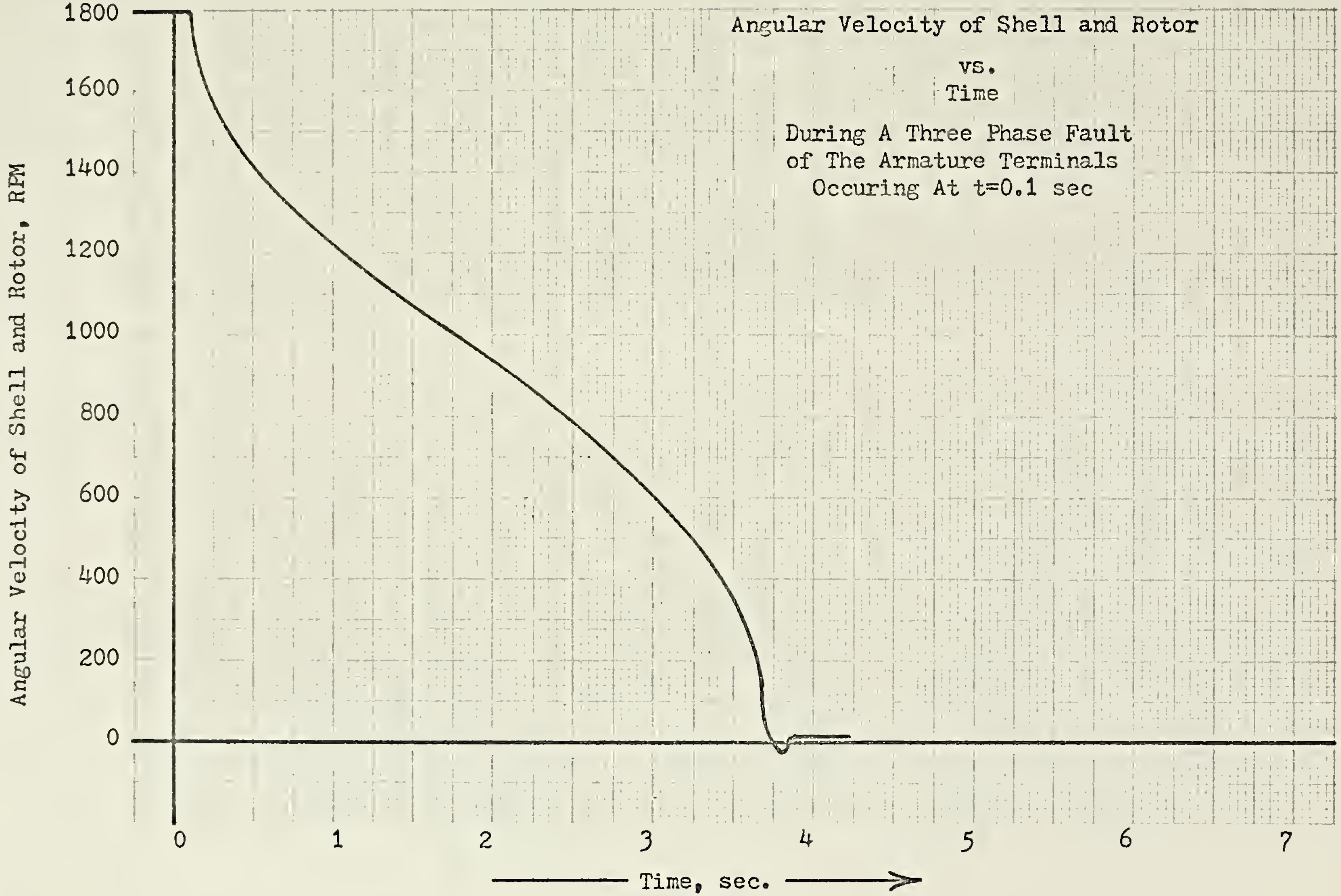
Time, sec.

Figure (17)



Angular Velocity of Shell and Rotor
vs.
Time
During A Crash Back
Occuring at t=0.1 sec
Angular Velocity of Shell and Rotor, RPM
1800
1600
1400
1200
1000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Time, sec

Figure (18)



Angular Velocity of Shell and Rotor
vs.
Time
During A Three Phase Fault
of The Armature Terminals
Occuring At t=0.1 sec
1800
1600
1400
1200
1000
800
600
400
200
0
Angular Velocity of Shell and Rotor, RPM
0
1
2
3
4
5
6
7
Time, sec.

Figure (19)

VIII DISCUSSION OF RESULTS AND CONCLUSIONS

Figures (4) through (15) demonstrate that the dual armature motor can be characterized by a set of steady state condition curves. These curves can assist in the rational selection of an operating condition for the motor. The data supplied by these curves can be cut many different ways; for instance, I_{fp} or T_{sp} could be considered as dependent variables and V_t or I_t could be treated as independent variables. In cutting the data different ways additional data points may be desirable, in this case the WATFIV program in Appendix (G) could be used if the appropriate parameters were adjusted.

Figures (16) through (19) provide the transient state results. Figure (16) shows that the rotor on start up under goes large angular velocity excursions with the attendant large acceleration forces. At one point the rotor actually runs backwards. Eventually the rotor settles down to its mechanical synchronous speed of 1800 RPM.

Figure (17) shows that for the shell start up there is some critical parameter R_{sp} between 10 pu and 20 pu where the shell starts up in a stable fashion at the fastest possible rate. For values of R_{sp} less than this critical value, the rotor tumbles or pulls out of synchronism with the stator field and results in a loss of starting torque and the introduction of a pulsating torque. For $R_{sp} = 0.588$ pu (its minimum value) the motor rotor does not start at all but oscillates about the zero point.

Figure (18) shows the crash back W_{sp} curve. The results of this curve beyond 1.8 seconds are questionable. The computer simulation appears to have gone astray at this point, perhaps due to too large of a step size in the simulation integration routine or due to the proximity of W_s

to zero. The rotor and shell both move at approximately the same velocity in this maneuver.

Figure (19) shows the three phase fault at the stator armature terminals. Again the computer simulation appears to go astray at about 3.7 seconds so results beyond that point are questionable.

The preliminary results of this thesis indicate that the dual armature super conducting motor is indeed a candidate for hydrofoil propulsion and warrants further investigation.

IX RECOMMENDATIONS

Additional areas that could be investigated using the equations developed in this thesis may be:

1. Determine steady state conditions as a function of R_{sp} . The present investigation considered $R_{sp} = 0.588$ pu in the steady state condition.

2. Write a computer program that will accept machine dimensions as input and return machine parameters for use in the steady state or transient analysis.

3. Instead of holding Ψ_{fp} constant as done in this thesis in the transient state investigation, hold I_{fp} constant.

4. Investigate current densities in the various windings during the transient periods to see if they exceed tolerable levels. Devise a scheme for controlling excess currents during transients.

5. Determine the static stability limit of rotor angle.

6. Refine load characteristics.

7. Vary machine dimensions to optimize the design. Criteria for optimizing could also be developed as a side issue.

8. Introdue hydrofoil dynamics into the model.

9. Investigate speed control by varying W_o the electrical frequency of the prime mover.

Most of these subject areas would apply at an under graduate project level.

Appendix A Shell Constraints

Equation sets (13), (14) and (15) contain parameters that are not independent. The following development assumes that flux leakages between adjacent circuits is negligible.

Assuming that the stator, shell and field axes are aligned so as to eliminate the sinusoidal dependency of the mutual inductances, the following relations can be written.

$$(L_s - M_{ss}) = \frac{3}{2} N_s^2 (P + \delta P_{ss})$$

$$L_r = N_r^2 (P + \delta P_{rr})$$

$$M_{as} = N_a N_s (P + \delta P_{as})$$

$$M_{ar} = N_a N_r (P + \delta P_{ar})$$

$$M_{af} = N_a N_f (P + \delta P_{af})$$

$$M_{sr} = N_s N_r (P + \delta P_{sr})$$

$$M_{sf} = N_s N_f (P + \delta P_{sf})$$

$$M_{rf} = N_r N_f (P + \delta P_{rf})$$

The $\frac{3}{2}$ factor appearing in the first equation is characteristic of three phase windings.

Now, if the various leakage permeances may be considered negligible and are set to zero, the above equations may be used to derive the following relations.

$$\frac{3}{2} M_{af} \left(L_a - M_{aa} \right) = \frac{3}{2} M_{sf} \cdot \frac{3}{2} M_{as}$$

$$\frac{3}{2} M_{ar} \left(L_a - M_{aa} \right) = \frac{3}{2} M_{sr} \cdot \frac{3}{2} M_{as}$$

$$M_{af} L_r = M_{rf} M_{ar}$$

These equations may now be per-unitized as follows:

$$\frac{3}{2} \frac{M_{af} W_o I_{ab}}{V_{fb}} \frac{(L_s - M_{ss}) W_o I_{sb}}{V_{sb}} = \frac{3}{2} \frac{M_{sf} W_o I_{sb}}{V_{fb}} \frac{3}{2} \frac{M_{as} W_o I_{ab}}{V_{sb}}$$

$$\frac{3}{2} \frac{M_{ar} W_o I_{ab}}{V_{rb}} \frac{(L_s - M_{ss}) W_o I_{sb}}{V_{sb}} = \frac{3}{2} \frac{M_{sr} W_o I_{sb}}{V_{rb}} \frac{3}{2} \frac{M_{as} W_o I_{ab}}{V_{sb}}$$

$$\frac{M_{af} W_o I_{fb}}{V_{ab}} \frac{L_r W_o I_{rb}}{V_{rb}} = \frac{M_{rf} W_o I_{fb}}{V_{rb}} \frac{M_{ar} W_o I_{rb}}{V_{ab}}$$

Comparing these relations with those in equation sets (10) and (13) it can be seen that the above relations reduce to;

$$X_s = X_{sf},$$

$$X_s = X_{sr} \text{ and}$$

$$X_r = X_{rf}.$$

Appendix B Derivation of Torque Expressions

The torque on any winding in per unit is given by

$$T_{ip} = (\Psi_{iq} I_{idp} - \Psi_{id} I_{iqp}).$$

Applying this to the stator and shell windings and substituting the expressions for current from equation Sets (21) and (22) and canceling terms where possible yields:

$$T_{ap} = \frac{X_o X_k}{W_o} (\Psi_{ad} \Psi_{sq} - \Psi_{aq} \Psi_{sd}) \quad \text{and}$$

$$T_{sp} = \frac{X_o}{W_o} (\Psi_{sd} \Psi_{rq} - \Psi_{sq} \Psi_{rd}) - T_{ap}$$

Also equilibrium of forces requires $T_{ap} + T_{sp} + T_{rp} = 0$.

Solving the above equations for the torque on the rotor gives

$$T_{rp} = \frac{X_o}{W_o} (\Psi_{sq} \Psi_{rd} - \Psi_{sd} \Psi_{rq}) .$$

Appendix C Motor Sizing

References (11) and (14) contain equations for the power rating of an air core, three phase synchronous motor. They can be simplified and adapted to the present application by assuming the following;

a. number of pole pairs = 2

b. winding angle of field = 120°

c. winding angle of shell = 60°

d. winding angle of stator = 60°

e. all winding electrical lengths= 1

f. the following parameters are defined as

$x = R_{ai}/R_{ao}$, $y = R_{fi}/R_{fo}$, and $z = R_{si}/R_{so}$. The radius dimensions are shown in figure (C-1).

The resulting power rating expression is,

$$P = 12\sqrt{6}\; 10^{-7} l\, W_o\, J_a\, J_f\, C_2\, R_{fo}^{\;4}\, (1 - y^4)\left(\frac{V_t}{E_f}\right)$$

where $C_2 = \frac{1}{8}\left(- \ln x + \frac{(1 - x^4)}{4} \left(\frac{R_{ao}}{R_{sh}} \right)^4\right)$,

$$\frac{V_t}{E_f} = - X_a \,\mathrm{SIN}(\gamma) = \sqrt{1 - X_a \,\mathrm{COS}^2(\gamma)} \;,$$

$\mathrm{COS}(\gamma)$ = power factor ,

$$X_a = \sqrt{0.375} \;\; \frac{J_a\, C_s}{J_f\, C_2\, (1 - y^4)} \left(\frac{R_{ao}}{R_{fo}} \right)^4,$$

and $C_s = \frac{1}{2}\left(x^4 \ln x + \frac{1 - x^4}{4} + \frac{(1 - x^4)^2}{8} \left(\frac{R_{ao}}{R_{sh}} \right)^4 \right).$

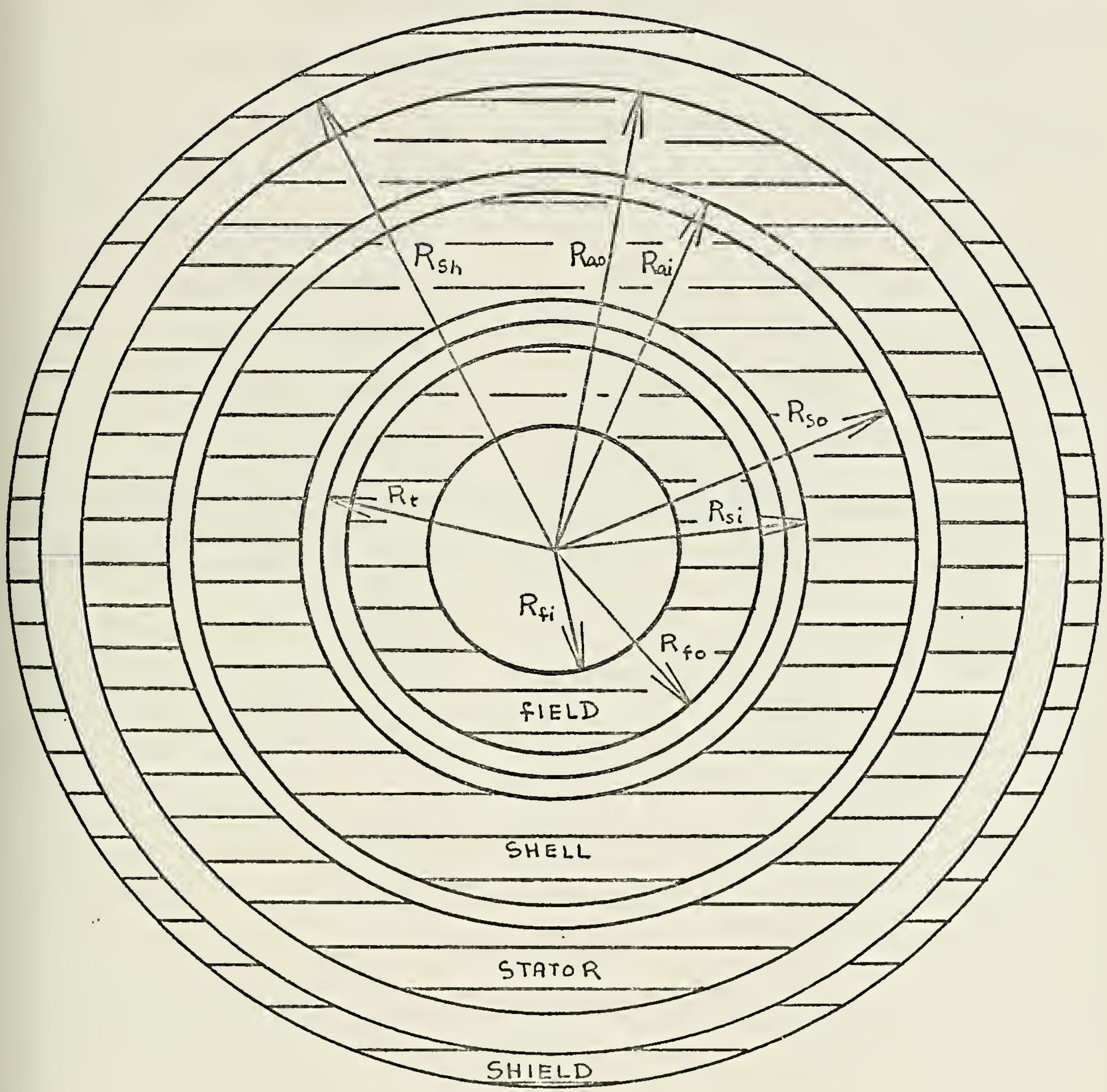


Figure (C - 1)

The current densities were chosen based on the values used in reference (11) and are; $J_a = 2.50 \times 10^6$ amps/meter^2 ,

and $J_f = 1.25 \times 10^8$ amps/meter^2 .

Synchronous electric frequency was chosen to be $W_o = 377$ radians/sec.

Power factor was chosen to be PF = 0.8 .

The power was chosen based on the requirements specified in reference (4) and is P = 21,000 horespower per motor.

The radii selected are;

$R_{fi} = 4.0$ inches	$R_{fo} = 6.5$ inches
$R_{si} = 7.5$ inches	$R_{so} = 10.5$ inches
$R_{ai} = 11.0$ inches	$R_{ao} = 13.5$ inches
$R_t = 7.0$ inches	$R_{sh} = 14.5$ inches

Finally, if the above assumptions are made and the power rating expression is solved for l, the result is l = 7.4 feet.

Appendix D Circuit and Mechanical Parameters of Motor

References (11) and (14) contain equations for determining the inductances (both self and mutual) for an air core, three phase, synchronous motor. These equations are infinite series summations; however, the lead term, n=1, dominates and all other terms are small. These equations can be simplified and adapted to the present application by assuming, in addition to the assumptions of appendix (C), that;

a. the leading term of the infinite series dominates,

b. the shield is made of magnetic iron and

c. the theory of superposition holds.

The resulting inductance expressions are listed in Table (D - 1). The dimensions are the same as discussed in appendix (C) and shown in figure (C - 1). If these dimensions are now used to solve the expressions in table (D - 1), table (D - 2) results.

If the expressions of table (D - 2) are per unitized using the base quantities of appendix (H), table (D - 3) results.

The definitions of X_j, X_k, X_1, X_m and X_o given on page 25 can now be evaluated and are;

$$X_j = 7.799$$

$$X_k = 3.685$$

$$X_1 = 4.685$$

$$X_o = 10.08$$

Reference (14) provides an equation for R_r and is

$$R_r = \frac{\pi \, 1 \, N_r^2}{4 \, \sigma_s \, R_t}$$

where $\sigma_s = \sigma \, t_d$, t_d being the damper shell thickness and σ being the

Table D-1 Inductances

$$L_a = \frac{18\, u_o\, N_a^2\, l}{\pi^3\, (1-X^2)^2} \left[X^4 \ln(x) + \frac{(1-X^4)}{4} + \frac{(1-X^4)^2}{8} \left(\frac{R_{ao}}{R_{sh}} \right)^4 \right]$$

$$L_s = \frac{18\, u_o\, N_s^2\, l}{\pi^3\, (1-Z^2)^2} \left[Z^4 \ln(Z) + \frac{(1-Z^4)}{4} + \frac{(1-Z^4)^2}{8} \left(\frac{R_{so}}{R_{sh}} \right)^4 \right]$$

$$L_r = \frac{\pi\, u_o\, N_r^2\, l}{16} \left[1 + \left(\frac{R_t}{R_{sh}} \right)^4 \right]$$

$$L_f = \frac{27\, u_o\, N_f^2\, l}{2\pi^3 (1-Y^2)^2} \left[Y^4 \ln(Y) + \frac{(1-Y^4)}{4} + \frac{(1-Y^4)^2}{8} \left(\frac{R_{fo}}{R_{sh}} \right)^4 \right]$$

$$M_{aa} = -\tfrac{1}{2} L_a$$

$$M_{as} = \frac{9}{\pi^3}\, u_o\, N_a\, N_s\, l\, \frac{(1+Z^2)}{(1-X^2)} \left(\frac{R_{so}}{R_{ao}} \right)^2 \left[-\ln(X) + \frac{(1-X^4)}{4} \left(\frac{R_{ao}}{R_{sh}} \right)^4 \right]$$

$$M_{ar} = \frac{3\, u_o\, N_a\, N_r\, l}{2\pi\, (1-X^2)} \left(\frac{R_t}{R_{ao}} \right)^2 \left[-\ln(X) + \frac{(1-X^4)}{4} \left(\frac{R_{ao}}{R_{sh}} \right)^4 \right]$$

$$M_{af} = \frac{9\sqrt{3}}{2\pi^3}\, u_o\, N_a\, N_f\, l\, \frac{(1+Y^2)}{(1-X^2)} \left(\frac{R_{fo}}{R_{ao}} \right)^2 \left[-\ln(X) + \frac{(1-X^4)}{4} \left(\frac{R_{ao}}{R_{sh}} \right)^4 \right]$$

Table D-1 Inductances (cont.)

$$M_{sr} = \frac{3\, u_o\, N_s\, N_r\, l}{2\pi\,(1-Z^2)} \left(\frac{R_t}{R_{so}} \right)^2 \left[-\ln(Z) + \frac{(1-Z^4)}{4} \left(\frac{R_{so}}{R_{sh}} \right)^4 \right]$$

$$M_{sf} = \frac{9\sqrt{3}}{2\pi^3}\, u_o\, N_s\, N_f\, l\, \frac{(1+Y^2)}{(1-Z^2)} \left(\frac{R_{fo}}{R_{so}} \right)^2 \left[-\ln(Z) + \frac{(1-Z^4)}{4} \left(\frac{R_{so}}{R_{sh}} \right)^4 \right]$$

$$M_{rf} = \frac{3\sqrt{3}}{16\pi}\, u_o\, N_r\, N_f\, l\, (1+Y^2) \left(\frac{R_{fo}}{R_t} \right) \left[1 + \left(\frac{R_t}{R_{sh}} \right) \right]$$

$$M_{ss} = -\tfrac{1}{2} L_s$$

Table D-2 Inductances

$$L_a = 5.104 \times 10^{-7} N_a^2 l$$

$$L_s = 3.532 \times 10^{-7} N_s^2 l$$

$$L_r = 2.601 \times 10^{-7} N_r^2 l$$

$$L_f = 2.101 \times 10^{-7} N_f^2 l$$

Table D-3 Per Unitized Inductances

$$X_a = 9.089$$

$$X_s = 19.23$$

$$X_r = 56.62$$

$$X_f = 112.4$$

conductivity of copper. Assuming $\sigma = 3.6 \times 10^7$ mhos/meter and $t_d = 0.11$ inches, $R_r = 4.42 \times 10^{-5} N_r^2 l$. Per unitizing using the base quantities of appendix (H) gives, $R_{rp} = 26.87$ pu.

In general, the resistance of a wound three phase winding is given by

$$R_i = \frac{4 N_i^2 l_i}{(R_{oi}^2 - R_{ii}^2)\, \theta_{wei}\, K_{si}\, \sigma_i} .$$

assuming the conductivity is $\sigma = 6 \times 10^7$ mhos/meter and the space factor $K_s = 0.27$ for both the shell and the stator armature, the per unitized resistances are; $R_{ap} = 0.200$ pu and $R_{sp} = 0.588$.

The resistance of the field winding is of course zero because it is made of a superconductor.

An initial estimate of the moments of inertia for the rotor and for the shell with shaft, propeller and entrained water included were;

$$J_s = 120 \text{ slug ft}^2 \quad \text{and} \quad J_r = 12 \text{ slug ft}^2$$

For H defined in the conventional manner, that is,

$$H_i = \frac{J_i W_b^2}{2 P_b}$$

$H_s = 0.738$ sec and $H = 0.0738$ sec.

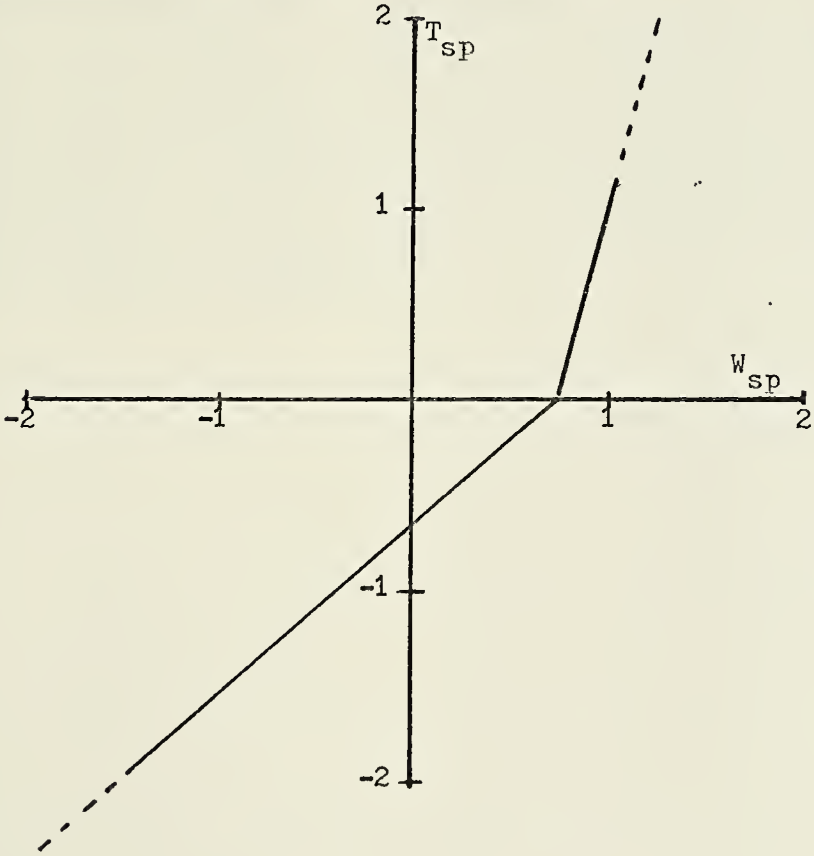
Note: the computer listings of appendix (G) show H to be different from the above values. This is because W_o was included so the value in the listings is 377 times smaller than the actual assumed value.

Appendix E Load Characteristics

The dynamics of the motor and propeller system are considered to be uncoupled from the hydrofoil dynamics for the time span of the simulations since the time constants of the two systems are quite different. Thus the load torque characteristics are a function of W_s alone.

For the shell start up, the propeller characteristics are assumed to be $T_{lp} = 5\,(W_s/W_o)^2$.

For the crash astern and the three phase fault, the load characteristics are assumed as shown below.



Appendix F Determination of Initial Conditions

An operating point was selected for the full power steady state from figures (4) through (15) as $s=0.0015$, $I_{fp}=1.0$ pu, and $T_{sp}=1.0$ pu. Then using the equations of equation set (26) a complete set of initial condition were determined and are listed in the computer listings in appendix (G).

For rotor start up, it was assumed that $T_{sp}=0.0$, $W_r=0.0$, $W_s=0.0$, and $\theta=0.0$. The remaining initial conditions were calculated using Equation Set (26) and are listed in the computer listings in appendix (G).

Part of the rotor start up computer simulation routine was to print out the final values of all the time variables at the end of the simulation period. These final values were then utilized as the initial conditions for the shell start up. The values are listed in the computer listings in appendix (G).

Appendix G Computer Program listings

```
/*MITID USER=(M10729,8938,,,YVCNNE)
// 'JOHN M SOLAN',CLASS=B,REGION=128K
/*SRI LOW
/*MAIN TIME=1,LINES=2
// EXEC WATFIV
//C.SYSIN DD *
$JOB              J    SOLAN
  100 FORMAT('1','IFP= ',F10.4)
  101 FORMAT('0','TORQUE= ',F10.4)
  102 FORMAT(' ',6F10.4)
  103 FORMAT('0',6X,'SLIP', 7X,'VTP', 7X,'ITP', 8X,'PF', 5X,'THETA', 7X,
     1 'ANG')
  104 FORMAT('0')
      REAL IADP, IAQP,IFP,ITP
      DATA WO/377./,XJ/7.799/,XK/3.685/,XL/4.685/,XO/10.0839/,RSP/.588/
      RAP=.2
      DO 1 K=1,3
      IFP=.6+.2*K
      DO 1 J=1,4
      TORQP=.25*J
      WRITE(6,100) IFP
      WRITE(6,101) TORQP
      WRITE(6,103)
      WRITE(6,104)
      DO 1 I=1,40
      S=.00025*I
      VADP=-WO/(XO*XK)*SQRT(S/RSP*TORQP)
      VAQP=-WO*IFP/(XO*XK)+(1.-XL)*RSP*XO*VADP/(S*WO)
      IADP=XO*XJ*VAQP/WO+(XO*XK/WO)**2.*RSP/S*VADP
      IAQP=-XO*XJ/WO*VADP
      PP=VADP*IADP+VAQP*IAQP
      QP=VAQP*IADP-VADP*IAQP
      PANG=ATAN(QP/PP)
      PF=COS(PANG)
      THETA=(-ATAN(VAQP/VADP)/3.1415927-1.)*180
      VAP=SQRT(VADP*VADP+VAQP*VAQP)
```

```
      ITP=SQRT(IADP*IADP+IAQP*IAQP)
      VTP=VAP+KAP*ITP
      WRITE(6,102) S,VTP,ITP,PF,THETA,PANG
    1 CONTINUE
      STOP
      END
$ENTRY
$STOP
/*
```

```
// 'JOHN M SOLAN',CLASS=A,REGION=130K
/*MITID USER=(M10729,6938,,,YVONNE)
/*SRI LOW
/*MAIN TIME=2,LINES=5
/*FORMAT  PR,DDNAME=COMPRINT
//JOBLIB DD DSNAME=SYS2.CSMP.LOAD,DISP=SHR
//   EXEC   PGM=IEFBR14
//DD1   DD   DSN=&&CSMP,UNIT=SYSDA,SPACE=(CYL,(1,1)),
//   DCB=(RECFM=F,LRECL=80,BLKSIZE=80),DISP=(NEW,PASS)
//   EXEC   PGM=IEFBR14
//DD2   DD   DSN=&&CSMP,DISP=(OLD,PASS)
//DD3   DD   VOL=REF=*.DD2,DSN=&&CSMP,DISP=(OLD,PASS)
//SHORT EXEC CSMP
//C.SYSLIN   DD   UNIT=,SPACE=,DCB=,DISP=(OLD,PASS)
//C.SYSLINK   DD   UNIT=,VOL=,DSN=&&CSMP
//C.SYSIN DD *
TITLE APPL OF SC MOTORS TO SCAV HYDROFOIL PROPULSION
*    VAQD = QUAD AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*    VADP = DIRECT AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*    A PREFIX 'D' INDICATES A TIME DERIVATIVE OF THAT VARIABLE
*    A SUFFIX 'IC' INDICATES THE INITIAL CONDITIONS OF THAT VARIABLE
*    SIAD = DIRECT AXIS STATOR ARMATURE FLUX IN PER UNIT
*    SIAQ = QUAD AXIS STATOR ARMATURE FLUX IN PER UNIT
*    SISD = DIRECT AXIS SHELL ARMATURE FLUX IN PER UNIT
*    SISQ = QUAD AXIS SHELL ARMATURE FLUX IN PER UNIT
*    SIRD = DIRECT AXIS ROTOR DAMPER FLUX IN PER UNIT
*    SIRQ = QUAD AXIS ROTOR DAMPER FLUX IN PER UNIT
*    SIF = SUPERCONDUCTING FIELD FLUX IN PER UNIT
*    VA = ABSOLUTE VALUE OF TERMINAL VOLTAGE OF ARMATURE IN PER UNIT
*    RSP = RESISTANCE OF SHELL ARMATURE IN PER UNIT
*    RRP = RESISTANCE OF ROTOR DAMPER IN PER UNIT
*    WO = SYNCH ELECTRIC FREQUENCY IN RADIANS (WILL NORMALLY BE 377)
*    WS = ANGULAR FREQUENCY OF SHELL ARMATURE
*    WR = ANGULAR FREQUENCY OF ROTOR
*    WTHTA = WR -WS
*    THTA = ANGLE IN RADIANS BETWEEN AXIS OF ROTOR AND ARMATURE VOLTAGE
```

```
*     TR = TORQUE ON ROTOR
*     TS = TORQUE ON SHELL
*     TL = LOAD TORQUE
*------------------------------------------------------------------------*
*                                                                        *
*          ROTOR START UP     SHELL CIRCUIT OPEN                         *
*                                                                        *
*------------------------------------------------------------------------*
INITIAL
PARAMETER SIF=112.96,WOF=377.,VAF=9.6918,RSF=.588,RRP=26.87,RAP=.2,...
XJ=7.799,XK=3.685,XL=4.685,XM=.6704,XO=10.064,HS=.002,HR=.0002
INCON SIADIC=9.134,SIAQIC=.0,SIRDIC=56.91,SIRQIC=.0,     ...
WRIC=.0,WSIC=.0,THTAIC=.0
DYNAMIC
VA=VAF
WO=WOF
VADP=VA*COS(THTA)
VAQP=-VA*SIN(THTA)
DSIAD=WOF*VADP+WR*SIAQ+RAP*XO*(XK*SISD-XJ*SIAD)
DSIAQ=WOF*VAQP-WR*SIAD+RAP*XO*(XK*SISQ-XJ*SIAQ)
DSIRD=    RRP*XO*(SISD-(1.+XM)*SIRD+XM*SIF)
DSIRQ=    RRP*XO*(SISQ-SIRQ)
SIAD=INTGRL(SIADIC,DSIAD)
SIAQ=INTGRL(SIAQIC,DSIAQ)
SISD=(XK*SIAD+SIRD)/XL
SISQ=(XK*SIAQ+SIRQ)/XL
SIRD=INTGRL(SIRDIC,DSIRD)
SIRQ=INTGRL(SIRQIC,DSIRQ)
WR=INTGRL(WRIC,AR)
WS=INTGRL(WSIC,AS)
WTHTA=WR-WO
THTA=INTGRL(THTAIC,WTHTA)
TR=XO*(SIRD*SISQ-SIRQ*SISD)/WOF
WPP=WS/WOF
TL=5.*WPP*ABS(WPP)
TM=SISD*SIAQ-SISQ*SIAD
```

```
TS=XO*XK*TM/WOF-TR-TL
AR=TR/(2.*HR)
AS=TS/(2.*HS)
TIMER DELT=.0002,FINTIM=2.,PRDEL=.005,OUTDEL=.005
METHOD SIMP
PRTPLT WR(WS,AR,AS)
TERMINAL
      WRITE(6,100)SIAD,SIAQ,SISD,SISQ,SIRD,SIRQ,THTA
 100  FORMAT(1X, 7E12.5   )
END
STOP
ENDJOB
```

```
// 'JOHN M SOLAN',CLASS=A,REGION=130K
/*MITID USER=(M10729,6938,,,YVONNE)
/*MAIN TIME=2,LINES=5
/*FORMAT  PR,DDNAME=COMPRINT
//JOBLIB DD DSNAME=SYS2.CSMP.LOAD,DISP=SHR
//   EXEC   PGM=IEFBR14
//DD1   DD   DSN=&&CSMP,UNIT=SYSDA,SPACE=(CYL,(1,1)),
//   DCB=(RECFM=F,LRECL=80,BLKSIZE=80),DISP=(NEW,PASS)
//   EXEC   PGM=IEFBR14
//DD2   DD   DSN=&&CSMP,DISP=(OLD,PASS)
//DD3   DD   VOL=REF=*.DD2,DSN=&&CSMP,DISP=(OLD,PASS)
//SHORT EXEC CSMP
//C.SYSLIN  DD  UNIT=,SPACE=,DCB=,DISP=(OLD,PASS)
//C.SYSLINK  DD  UNIT=,VOL=,DSN=&&CSMP
//C.SYSIN DD *
TITLE APPL OF SC MOTORS TO SCAV HYDROFOIL PROPULSION
*     VAQD = QUAD AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*     VADP = DIRECT AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*     A PREFIX 'D' INDICATES A TIME DERIVATIVE OF THAT VARIABLE
*     A SUFFIX 'IC' INDICATES THE INITIAL CONDITIONS OF THAT VARIABLE
*     SIAD = DIRECT AXIS STATOR ARMATURE FLUX IN PER UNIT
*     SIAQ = QUAD AXIS STATOR ARMATURE FLUX IN PER UNIT
*     SISD = DIRECT AXIS SHELL ARMATURE FLUX IN PER UNIT
*     SISQ = QUAD AXIS SHELL ARMATURE FLUX IN PER UNIT
*     SIRD = DIRECT AXIS ROTOR DAMPER FLUX IN PER UNIT
*     SIRQ = QUAD AXIS ROTOR DAMPER FLUX IN PER UNIT
*     SIF = SUPERCONDUCTING FIELD FLUX IN PER UNIT
*     VA = ABSOLUTE VALUE OF TERMINAL VOLTAGE OF ARMATURE IN PER UNIT
*     RSP = RESISTANCE OF SHELL ARMATURE IN PER UNIT
*     RRP = RESISTANCE OF ROTOR DAMPER IN PER UNIT
*     WO = SYNCH ELECTRIC FREQUENCY IN RADIANS (WILL NORMALLY BE 377)
*     WS = ANGULAR FREQUENCY OF SHELL ARMATURE
*     WR = ANGULAR FREQUENCY OF ROTOR
*     WTHTA = WR -WS
*     THTA = ANGLE IN RADIANS BETWEEN AXIS OF ROTOR AND ARMATURE VOLTAGE
*     TR = TORQUE ON ROTOR
```

```
*     TS = TORQUE ON SHELL
*     TL = LOAD TORQUE
*--------------------------------------------------------------------------*
*                                                                          *
*         SHELL START UP    ROTOR RUNNING AT SYNCH SPEED                   *
*                                                                          *
*--------------------------------------------------------------------------*
INITIAL
PARAMETER SIF=112.96,WOF=377.,VAF=9.6918,RSF=.588,RRP=26.87,RAP=.2,...
XJ=7.759,XK=3.665,XL=4.685,XM=.6704,XO=10.084,HS=.002,HR=.0002
PARAMETER RSP=(20.,40.,60.,80.)
INCON SIADIC=9.6782,SIAQIC=.29709,SISDIC=19.823,SISQIC=.09782, ...
SIRDIC=57.203,SIRQIC=.086492,WRIC=377.7,WSIC=9.6599,THTAIC=-14.166
DYNAMIC
VA=VAF
WO=WOF
VADP=VA*COS(THTA)
VAQP=-VA*SIN(THTA)
DSIAD=WOF*VADP+WR*SIAQ+RAP*XO*(XK*SISD-XJ*SIAD)
DSIAQ=WOF*VAQP-WR*SIAD+RAP*XO*(XK*SISQ-XJ*SIAQ)
DSISD=WN*SISQ+    RSP*XO*(XK*SIAD-XL*SISD+SIRD)
DSISQ=-WN*SISD+   RSP*XO*(XK*SIAQ-XL*SISQ+SIRQ)
DSIRD=    RRP*XO*(SISD-(1.+XM)*SIRD+XM*SIF)
DSIRQ=    RRP*XO*(SISQ-SIRQ)
SIAD=INTGRL(SIADIC,DSIAD)
SIAQ=INTGRL(SIAQIC,DSIAQ)
SISD=INTGRL(SISDIC,DSISD)
SISQ=INTGRL(SISQIC,DSISQ)
SIRD=INTGRL(SIRDIC,DSIRD)
SIRQ=INTGRL(SIRQIC,DSIRQ)
WR=INTGRL(WRIC,AR)
WS=INTGRL(WSIC,AS)
WN=WR-WS
WTHTA=WR-WO
THTA=INTGRL(THTAIC,WTHTA)
TR=XO*(SIRD*SISQ-SIRQ*SISD)/WOF
```

```
WPP=WS/WOF
TL=5.*WPP*ABS(WPP)
TM=SISD*SIAQ-SISQ*SIAD
TS=XO*XK*TM/WOF-TR-TL
AR=TR/(2.*HR)
AS=TS/(2.*HS)
BETA=THTA
TIMER DELT=.0001,FINTIM =2.,PRDEL=.01,OUTDEL=.01
FINISH THTA=-1000. ,BETA=1000.
METHOD SIMP
PRTPLT WS(WR,THTA,AR)
TERMINAL
      WRITE(6,100) AR,AS,WR,WS,SIAD,SIAQ,SISD,SISQ,SIRD,SIRQ
 100  FORMAT(1X,10E12.5)
END
STOP
ENDJOB
```

```
// 'JOHN M SOLAN',CLASS=A,REGION=130K
/*MITID USER=(M10729,8938,,,YVONNE)
/*MAIN TIME=2,LINES=5
/*FORMAT  PR,DDNAME=COMPRINT
//JOBLIB DD DSNAME=SYS2.CSMP.LOAD,DISP=SHR
//   EXEC  PGM=IEFBR14
//DD1  DD   DSN=&&CSMP,UNIT=SYSDA,SPACE=(CYL,(1,1)),
//   DCB=(RECFM=F,LRECL=80,BLKSIZE=80),DISP=(NEW,PASS)
//   EXEC  PGM=IEFBR14
//DD2  DD   DSN=&&CSMP,DISP=(OLD,PASS)
//DD3  DD   VOL=REF=*.DD2,DSN=&&CSMP,DISP=(OLD,PASS)
//SHORT EXEC CSMP
//C.SYSLIN  DD  UNIT=,SPACE=,DCB=,DISP=(OLD,PASS)
//C.SYSLINK  DD  UNIT=,VOL=,DSN=&&CSMP
//C.SYSIN DD *
TITLE APPL OF SC MOTORS TO SCAV HYDROFOIL PROPULSION
*    VAQD = QUAD AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*    VADP = DIRECT AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*    A PREFIX 'D' INDICATES A TIME DERIVATIVE OF THAT VARIABLE
*    A SUFFIX 'IC' INDICATES THE INITIAL CONDITIONS OF THAT VARIABLE
*    SIAD = DIRECT AXIS STATOR ARMATURE FLUX IN PER UNIT
*    SIAQ = QUAD AXIS STATOR ARMATURE FLUX IN PER UNIT
*    SISD = DIRECT AXIS SHELL ARMATURE FLUX IN PER UNIT
*    SISQ = QUAD AXIS SHELL ARMATURE FLUX IN PER UNIT
*    SIRD = DIRECT AXIS ROTOR DAMPER FLUX IN PER UNIT
*    SIRQ = QUAD AXIS ROTOR DAMPER FLUX IN PER UNIT
*    SIF = SUPERCONDUCTING FIELD FLUX IN PER UNIT
*    VA = ABSOLUTE VALUE OF TERMINAL VOLTAGE OF ARMATURE IN PER UNIT
*    RSP = RESISTANCE OF SHELL ARMATURE IN PER UNIT
*    RRP = RESISTANCE OF ROTOR DAMPER IN PER UNIT
*    WJ = SYNCH ELECTRIC FREQUENCY IN RADIANS (WILL NORMALLY BE 377)
*    WS = ANGULAR FREQUENCY OF SHELL ARMATURE
*    WR = ANGULAR FREQUENCY OF ROTOR
*    WTHTA = WR -WS
*    THTA = ANGLE IN RADIANS BETWEEN AXIS OF ROTOR AND ARMATURE VOLTAGE
*    TR = TORQUE ON ROTOR
```

```
*     TS = TORQUE ON SHELL
*     TL = LOAD TORQUE
*-----------------------------------------------------------------------*
*                                                                       *
*         SHELL START UP   ROTOR RUNNING AT SYNCH SPEED                 *
*                                                                       *
*-----------------------------------------------------------------------*
INITIAL
PARAMETER SIF=112.96,WOF=377.,VAF=9.6918,RSF=.588,RRP=26.87,RAP=.2,...
XJ=7.795,XK=3.685,XL=4.685,XM=.6704,XO=10.084,HS=.002,HR=.0002
INCON SIADIC=9.673,SIAQIC=.0,SISDIC=13.46,SISQIC=.0,SIRDIC=27.22,...
SIRQIC=.0,THTAIC=-1.571,WRIC=377.,WSIC=.0
DYNAMIC
VA=VAF
WO=WOF
VADP=VA*COS(THTA)
VAQP=-VA*SIN(THTA)
RSP=1000.
DSIAD=WOF*VADP+WR*SIAQ+RAP*XO*(XK*SISD-XJ*SIAD)
DSIAQ=WOF*VAQP-WR*SIAD+RAP*XO*(XK*SISQ-XJ*SIAQ)
DSISD=WN*SISQ+    RSP*XO*(XK*SIAD-XL*SISD+SIRD)
DSISQ=-WN*SISD+    RSP*XO*(XK*SIAQ-XL*SISQ+SIRQ)
DSIRD=    RRP*XO*(SISD-(1.+XM)*SIRD+XM*SIF)
DSIRQ=    RRP*XO*(SISQ-SIRQ)
SIAD=INTGRL(SIADIC,DSIAD)
SIAQ=INTGRL(SIAQIC,DSIAQ)
SISD=INTGRL(SISDIC,DSISD)
SISQ=INTGRL(SISQIC,DSISQ)
SIRD=INTGRL(SIRDIC,DSIRD)
SIRQ=INTGRL(SIRQIC,DSIRQ)
WR=INTGRL(WRIC,AR)
WS=INTGRL(WSIC,AS)
WN=WR-WS
WTHTA=WR-WO
THTA=INTGRL(THTAIC,WTHTA)
TR=XO*(SIRD*SISQ-SIRQ*SISD)/WOF
```

```
WPP=WS/WCF
TL=5.*WPP*ABS(WPP)
TM=SISD*SIAQ-SISQ*SIAD
TS=XO*XK*TM/WCF-TR-TL
AR=TR/(2.*HR)
AS=TS/(2.*HS)
TIMER DELT=.0002,FINTIM=.5,PRDEL=.005,OUTDEL=.005
METHOD SIMP
PRTPLT WS(WR,AR,AS)
END
STOP
ENDJOB
```

```
// 'JOHN M SOLAN',CLASS=A,REGION=130K
/*MITID USER=(M10729,6938,,,YVCNNE)
/*MAIN TIME=1,LINES=5
/*FORMAT  PR,DDNAME=COMPRINT
//JOBLIB DD DSNAME=SYS2.CSMP.LOAD,DISP=SHR
//   EXEC   PGM=IEFBR14
//DD1   DD   DSN=&&CSMP,UNIT=SYSDA,SPACE=(CYL,(1,1)),
//   DCB=(RECFM=F,LRECL=80,BLKSIZE=80),DISP=(NEW,PASS)
//   EXEC   PGM=IEFBR14
//DD2   DD   DSN=&&CSMP,DISP=(OLD,PASS)
//DD3   DD   VOL=REF=*.DD2,DSN=&&CSMP,DISP=(OLD,PASS)
//SHORT EXEC CSMP
//C.SYSLIN   DD   UNIT=,SPACE=,DCB=,DISP=(OLD,PASS)
//C.SYSLINK   DD   UNIT=,VOL=,DSN=&&CSMP
//C.SYSIN DD *
TITLE APPL OF SC MOTORS TO SCAV HYDROFOIL PROPULSION
*     VAQD = QUAD AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*     VADP = DIRECT AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*     A PREFIX 'D' INDICATES A TIME DERIVATIVE OF THAT VARIABLE
*     A SUFFIX 'IC' INDICATES THE INITIAL CONDITIONS OF THAT VARIABLE
*     SIAD = DIRECT AXIS STATOR ARMATURE FLUX IN PER UNIT
*     SIAQ = QUAD AXIS STATOR ARMATURE FLUX IN PER UNIT
*     SISD = DIRECT AXIS SHELL ARMATURE FLUX IN PER UNIT
*     SISQ = QUAD AXIS SHELL ARMATURE FLUX IN PER UNIT
*     SIRD = DIRECT AXIS ROTOR DAMPER FLUX IN PER UNIT
*     SIRQ = QUAD AXIS ROTOR DAMPER FLUX IN PER UNIT
*     SIF = SUPERCONDUCTING FIELD FLUX IN PER UNIT
*     VA = ABSOLUTE VALUE OF TERMINAL VOLTAGE OF ARMATURE IN PER UNIT
*     RSP = RESISTANCE OF SHELL ARMATURE IN PER UNIT
*     RRP = RESISTANCE OF ROTOR DAMPER IN PER UNIT
*     WO = SYNCH ELECTRIC FREQUENCY IN RADIANS (WILL NORMALLY BE 377)
*     WS = ANGULAR FREQUENCY OF SHELL ARMATURE
*     WR = ANGULAR FREQUENCY OF ROTOR
*     WTHTA = WR -WS
*     THTA = ANGLE IN RADIANS BETWEEN AXIS OF ROTOR AND ARMATURE VOLTAGE
*     TR = TORQUE ON ROTOR
```

```
*     TS = TORQUE ON SHELL
*     TL = LOAD TORQUE
*------------------------------------------------------------------------*
*                                                                        *
*          CRASH BACK FROM FULL AHEAD                                    *
*                                                                        *
*------------------------------------------------------------------------*
INITIAL
PARAMETER SIF=112.96,WOF=377.,VAF=9.6918,RSP=.586,RRP=26.87,RAP=.2,...
XJ=7.799,XK=3.585,XL=4.685,XM=.6704,XO=10.084,HS=.002,HR=.0002
INCON SIADIC=9.673,SIAQIC=.51276,SISDIC=19.814,SISQIC=.0,...
SIRDIC=37.197,SIRQIC=0.,WRIC=376.99,WSIC=376.426,THTAIC=-1.6237
FUNCTION TORQL=-2000,-1750,-2.75,-3.,.75,0.,2.,5.,1100.,4400.
DYNAMIC
VA=VAF
WO=WOF*(1.-2.*STEP( .1))
VAOP=VA*COS(THTA)
VAQP=-VA*SIN(THTA)
DSIAD=WOF*VADP+WR*SIAQ+RAP*XO*(XK*SISD-XJ*SIAD)
DSIAQ=WOF*VAQP-WR*SIAD+RAP*XO*(XK*SISQ-XJ*SIAQ)
DSISD=WN*SISQ+    RSP*XO*(XK*SIAD-XL*SISD+SIRD)
DSISQ=-WN*SISD+    RSP*XO*(XK*SIAQ-XL*SISQ+SIRQ)
DSIRD=    RRP*XO*(SISD-(1.+XM)*SIRD+XM*SIF)
DSIRQ=    RRP*XJ*(SISQ-SIRQ)
SIAD=INTGRL(SIADIC,DSIAD)
SIAQ=INTGRL(SIAQIC,DSIAQ)
SISD=INTGRL(SISDIC,DSISD)
SISQ=INTGRL(SISQIC,DSISQ)
SIRD=INTGRL(SIRDIC,DSIRD)
SIRQ=INTGRL(SIRQIC,DSIRQ)
WR=INTGRL(WRIC,AR)
WS=INTGRL(WSIC,AS)
WN=WR-WS
WTHTA=WR-WO
THTA=INTGRL(THTAIC,WTHTA)
TR=XO*(SIRD*SISQ-SIRQ*SISD)/WOF
```

```
WPP=WS/WOF
TL= AFGEN(TORQL,WPP)
TM=SISD*SIAQ-SISQ*SIAD
TS=XO*XK*TM/WOF-TR-TL
AR=TR/(2.*HR)
AS=TS/(2.*HS)
TIMER DELT=.0002,FINTIM=2.,PRDEL=.005,OUTDEL=.005
METHOD SIMP
PRTPLT WS(WR,AR,AS)
END
STOP
ENDJOB
```

```
// 'JOHN M SOLAN',CLASS=A,REGION=130K
/*MITID USER=(M10729,8938,,,YVONNE)
/*MAIN TIME=2,LINES=5
/*FORMAT   PR,DDNAME=COMPRINT
//JOBLIB DD DSNAME=SYS2.CSMP.LOAD,DISP=SHR
//   EXEC   PGM=IEFBR14
//DD1   DD   DSN=&&CSMP,UNIT=SYSDA,SPACE=(CYL,(1,1)),
//   DCB=(RECFM=F,LRECL=80,BLKSIZE=80),DISP=(NEW,PASS)
//   EXEC   PGM=IEFBR14
//DD2   DD   DSN=&&CSMP,DISP=(OLD,PASS)
//DD3   DD   VOL=REF=*.DD2,DSN=&&CSMP,DISP=(OLD,PASS)
//SHORT EXEC CSMP
//C.SYSLIN   DD   UNIT=,SPACE=,DCB=,DISP=(OLD,PASS)
//C.SYSLINK   DD   UNIT=,VOL=,DSN=&&CSMP
//C.SYSIN DD *
TITLE APPL OF SC MOTORS TO SCAV HYDROFOIL PROPULSION
*     VAQD = QUAD AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*     VADP = DIRECT AXIS COMPONENT OF ARMATURE TERMINAL VOLTAGE
*     A PREFIX 'D' INDICATES A TIME DERIVATIVE OF THAT VARIABLE
*     A SUFFIX 'IC' INDICATES THE INITIAL CONDITIONS OF THAT VARIABLE
*     SIAD = DIRECT AXIS STATOR ARMATURE FLUX IN PER UNIT
*     SIAQ = QUAD AXIS STATOR ARMATURE FLUX IN PER UNIT
*     SISD = DIRECT AXIS SHELL ARMATURE FLUX IN PER UNIT
*     SISQ = QUAD AXIS SHELL ARMATURE FLUX IN PER UNIT
*     SIRD = DIRECT AXIS ROTOR DAMPER FLUX IN PER UNIT
*     SIRQ = QUAD AXIS ROTOR DAMPER FLUX IN PER UNIT
*     SIF = SUPERCONDUCTING FIELD FLUX IN PER UNIT
*     VA = ABSOLUTE VALUE OF TERMINAL VOLTAGE OF ARMATURE IN PER UNIT
*     RSP = RESISTANCE OF SHELL ARMATURE IN PER UNIT
*     RRP = RESISTANCE OF ROTOR DAMPER IN PER UNIT
*     WO = SYNCH ELECTRIC FREQUENCY IN RADIANS (WILL NORMALLY BE 377)
*     WS = ANGULAR FREQUENCY OF SHELL ARMATURE
*     WR = ANGULAR FREQUENCY OF ROTOR
*     WTHTA = WR -WS
*     THTA = ANGLE IN RADIANS BETWEEN AXIS OF ROTOR AND ARMATURE VOLTAGE
*     TR = TORQUE ON ROTOR
```

```
*     TS = TORQUE ON SHELL
*     TL = LOAD TORQUE
*-----------------------------------------------------------------------*
*                                                                       *
*          THREE PHASE SHORT AT MOTOR TERMINALS                         *
*                                                                       *
*                                                                       *
*-----------------------------------------------------------------------*
INITIAL
PARAMETER SIF=112.96,WOF=377.,VAF=9.6918,RSP=.588,RRP=26.87,RAP=.2,...
XJ=7.759,XK=5.605,XL=4.685,XM=.6704,XO=10.084,HS=.002,HR=.0002
INCON SIADIC=9.673,SIAQIC=.51276,SISDIC=19.814,SISQIC=.0,...
SIRDIC=57.197,SIRQIC=0.,WRIC=376.99,WSIC=376.426,THTAIC=-1.6237
FUNCTION TORQL=-2000,-1750,-2.75,-3.,.75,0.,2.,5.,1100.,4400.
DYNAMIC
VA=VAF*(1.-STEP( 0.1))
WO=WOF
VADP=VA*COS(THTA)
VAQP=-VA*SIN(THTA)
DSIAD=WOF*VADP+WR*SIAQ+RAP*XO*(XK*SISD-XJ*SIAD)
DSIAQ=WOF*VAQP-WR*SIAD+RAP*XO*(XK*SISQ-XJ*SIAQ)
DSISD=WN*SISQ+    RSP*XO*(XK*SIAD-XL*SISD+SIRD)
DSISQ=-WN*SISD+    RSP*XO*(XK*SIAQ-XL*SISQ+SIRQ)
DSIRD=    RRP*XO*(SISD-(1.+XM)*SIRD+XM*SIF)
DSIRQ=    RRP*XO*(SISQ-SIRQ)
SIAD=INTGRL(SIADIC,DSIAD)
SIAQ=INTGRL(SIAQIC,DSIAQ)
SISD=INTGRL(SISDIC,DSISD)
SISQ=INTGRL(SISQIC,DSISQ)
SIRD=INTGRL(SIRDIC,DSIRD)
SIRQ=INTGRL(SIRQIC,DSIRQ)
WR=INTGRL(WRIC,AR)
WS=INTGRL(WSIC,AS)
WN=WR-WS
WTHTA=WR-WO
THTA=INTGRL(THTAIC,WTHTA)
```

```
TR=XO*(SIRD*SISQ-SIRQ*SISD)/WOF
WPP=WS/WOF
TL= AFGEN(TORQL,WPP)
TM=SISD*SIAQ-SISQ*SIAD
TS=XO*XK*TM/WOF-TR-TL
AS=TS/(2.*HS)
AR=TR/(2.*HR)
TIMER DELT=.0004,FINTIM=4.,PRDEL=.005,OUTDEL=.005
METHOD SIMP
PRTPLT WS(WR,AR,AS)
END
STOP
ENDJOB
```

Appendix H Base Quantity Selections

As mentioned on page (21), two remaining base parameters are free to be selected. The bases selected are;

1) P_b = 21,000 horsepower and

2) I_{fp} = 1.0 pu when $J_f = 1.25 \times 10^8$ amps/meter^2.

At this point eight conditions have been specified on the eight base quantities so the base system is fully constrained and all base quantities can be calculated. They are;

$V_{ab} = 19.36\ N_a$ volts $I_{ab} = 2.696 \times 10^5$ amps/N_a

$V_{sb} = 11.65\ N_s$ volts $I_{sb} = 4.479 \times 10^5$ amps/N_s

$V_{rb} = 5.640\ N_r$ volts $I_{rb} = 1.388 \times 10^6$ amps/N_r

$V_{fb} = 3.531\ N_f$ volts $I_{fb} = 2.217 \times 10^6$ amps/N_f

REFERENCES

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4. "Superconducting Machinery for Ship Propulsion Systems, "S. T. W. Liang and L. F. Martin, <u>Naval Ship Research and Development Center Report 3787</u>, March 1972.
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